

COGNITIVE CONTROL IN AGE-RELATED HEARING LOSS

BY

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DISSERTATION

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ABSTRACT

Purpose: Growing evidence suggests that cognitive changes occur in individuals with age-related hearing loss (ARHL), with earliest changes in cognitive control. Cognitive control refers to a broad class of mental operations that allow goal-directed behavior and includes processes of cognitive flexibility, inhibitory control, and working memory updating. Cognitive control is critical for everyday activities, including the ability to recognize speech in noisy environments, which is challenging for individuals with ARHL. Few studies have systematically investigated alterations in various cognitive control processes in individuals with unaided mild ARHL and how these processes relate to speech-in-noise (SiN) recognition. The primary goal of this dissertation was to investigate cognitive control changes in individuals with unaided mild ARHL. The secondary goal was to examine associations between SiN recognition and cognitive control processes.

Method: Three studies were conducted to examine cognitive control in individuals with ARHL. The findings of each study informed the goal of the next. The first study reviewed literature on associations between hearing ability and three cognitive control processes (cognitive flexibility, inhibitory control, and working memory updating) in individuals with ARHL and the links between SiN recognition and these cognitive control processes. The second study examined behavioral alterations in cognitive flexibility and inhibitory control in individuals with unaided mild ARHL relative to age- and education-matched normal hearing (NH) controls. Additionally, associations between SiN recognition and cognitive flexibility and inhibitory control were explored. The final study used event-related electroencephalography to examine neural alterations in inhibitory control in individuals with unaided mild ARHL relative to NH controls and the links between SiN recognition and neural correlates of inhibitory control.

Results/Discussion: The literature review revealed consistent evidence for associations between hearing ability and cognitive flexibility/working memory updating involving complex tasks in individuals with ARHL. Whereas, evidence for association between hearing ability and inhibitory control was mixed. In general, working memory updating has been more extensively studied in individuals with ARHL compared to cognitive flexibility and inhibitory control. Also, very few have examined multiple cognitive control processes in older adults with unaided mild ARHL in the same study. Studies two and three revealed behavioral and neural alterations in inhibitory control in older adults with unaided mild ARHL relative to age-matched NH controls. Additionally, worse SiN recognition was related to greater alterations in cognitive flexibility and inhibitory control. Overall, the findings suggest that inhibitory control alterations are noted even in those with unaided mild ARHL and these go above and beyond typical aging-related cognitive changes. Furthermore, our work suggests that cognitive flexibility and inhibitory control are critical for listening in complex environments in older adults, including those with mild ARHL. This dissertation contributes knowledge that informs clinical practice related to individuals with mild ARHL and supports theoretical postulations that suggest neural alterations related to changes in cognition in ARHL.

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TABLE OF CONTENTS

Chapter 1. General Introduction.....	1
1.1. Background.....	1
1.2. Outline of Dissertation.....	4
1.3. References.....	6
Chapter 2. A Narrative Review of Cognitive Control in Age-Related Hearing Loss.....	15
2.1. Introduction.....	16
2.2. Methods.....	17
2.3. Relationship between Peripheral Hearing Acuity and Cognitive Control in Individuals with Age-Related Hearing Loss.....	20
2.4. Relationship between SiN Recognition and Cognitive Control in Individuals with Age-Related Hearing Loss.....	31
2.5. Summary and Conclusion.....	38
2.6. Tables and Figures.....	42
2.7. References.....	57
Chapter 3. Cognitive Flexibility and Inhibitory Control in Age-Related Hearing Loss.....	76
3.1. Introduction.....	77
3.2. Materials and Methods.....	81
3.3. Results.....	88
3.4. Discussion.....	90
3.5. Tables and Figures.....	98
3.6. References.....	102
3.7. Supplementary Materials.....	120
Chapter 4. Neurophysiological Alterations in Inhibitory Control in Mild Age-Related Hearing Loss.....	125
4.1. Introduction.....	126
4.2. Materials and Methods.....	136
4.3. Results.....	146
4.4. Discussion.....	151
4.5. Tables and Figures.....	158
4.6. References.....	178
Chapter 5. Summary and Future Directions.....	198
5.1. Summary.....	198
5.2. Clinical Implications and Future Directions.....	202

5.3. Figures.....	204
5.4. References.....	206

Chapter 1. General Introduction

1.1. Background

Recently, the Global Burden of Diseases, Injuries, and Risk Factors Study found hearing loss to be the third leading cause of years lived with disability and a major concern for global health, especially in older adults (Vos et al., 2017). Age-related hearing loss (ARHL) is a common condition with gradual loss of hearing due to aging. In the United States, approximately one in three adults between 65 and 74 years of age, and nearly half of those over 75 years of age have ARHL (National Institute on Deafness and Other Communication Disorders, 2016). Decades of research have documented several auditory deficits in individuals with ARHL, including alterations in detection, discrimination, recognition, and comprehension of sounds (Akeroyd, 2008; CHABA, 1988; Chmiel & Jerger, 1996) with recognition of speech-in-noise (SiN) being a big concern (Akeroyd, 2008; CHABA, 1988; Chmiel & Jerger, 1996; Gates & Mills, 2005; Humes, 1996, 2013, 2020; Jerger et al., 1989; Jerger, 1992; Jerger et al., 1995; Kim & Yeo, 2015; Sardone et al., 2019). Apart from deficits in sound processing and speech recognition, growing evidence suggests alterations in other cognitive processes in ARHL (Akeroyd, 2008; Boxtel et al., 2003; Bucks et al., 2016; Guerreiro & Van Gerven, 2017; Hällgren et al., 2001; Humes, 2007, 2013; Lin, 2011; Lin, et al., 2011, 2013; Pichora-Fuller, 2003, 2015).

Evidence for a link between sensory perception and cognition in older adults was first documented by two noted cognitive psychologists, Lindenberger and Baltes in the 1990s (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). They found that age-related variance in cognition was significantly explained by sensory measures of peripheral hearing and visual acuity. Over the years, three hypotheses have been put forth to explain why cognition might be

impaired in individuals with ARHL. These include information-degradation (CHABA, 1988; Schneider & Pichora-Fuller, 2000), sensory-deprivation (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994), and the common-cause (Baltes & Lindenberger, 1997; CHABA, 1988; Lindenberger & Baltes, 1994) hypotheses. According to the information-degradation hypothesis, individuals with ARHL experience cognitive alterations because mental resources meant for higher-level cognitive tasks get diverted to aid sound perception. These cognitive changes are proposed to be temporary and reversible. On the other hand, the sensory-deprivation hypothesis suggests permanent cognitive changes. It proposes that “protracted sensory underload”, or long-term hearing loss, leads to constant reallocation of mental resources to support auditory perception, and over time, this chronic reallocation leads to permanent cognitive decline. Taken together, both the information-degradation and sensory-deprivation hypotheses suggest resource allocation challenges contribute to cognitive alterations in ARHL, with the mechanistic bases at the neural level (Uchida et al., 2019; Wayne & Johnsrude, 2015). The third hypothesis, the common-cause, proposes that a third common factor, which is aging, leads to both ARHL and cognitive decline in older adults. In particular, the cognitive alterations in older adults with ARHL are proposed to occur due to aging-related neurodegenerative changes which are also responsible for the deficits in auditory functions (Baltes & Lindenberger, 1997; Wayne & Johnsrude, 2015).

At their core, all three hypotheses suggest that cognitive alterations in older adults with ARHL result from alterations in underlying neural structures and functions. Neuroimaging studies have provided evidence for neural changes in individuals with ARHL. Studies using structural magnetic resonance imaging (MRI) have found that the severity of ARHL is associated with reductions in gray matter volume of the primary auditory cortices (Eckert et al., 2012, 2019;

Husain et al., 2011; Lin et al., 2014) as well as the hippocampus, insula, and frontal cortices (Husain et al., 2011; Lin et al., 2014; for review see Slade et al., 2020). These findings suggest cortical alterations in brain regions responsible for auditory functions as well as non-auditory cognitive functions. Studies using diffusion tensor imaging (DTI), a technique that analyzes structural MRI data for the diffusion of water molecules in biological tissues have found white matter alterations in ARHL. More diffuse transmission has been noted in several white matter tracts leading into and out of the auditory cortex (Husain et al., 2011), and in Heschl's gyrus (Ma et al., 2016; Profant et al., 2014) in older adults with ARHL as compared to normal hearing (NH) controls. Functional magnetic resonance imaging (fMRI) studies have found greater activation in prefrontal cortices of older adults with ARHL during SiN recognition task compared to NH individuals, providing support for alterations in neural functions that are above and beyond what is typically observed in normal aging (Du et al., 2016; Rosemann & Thiel, 2020).

Over the years, research on cognitive changes in ARHL has grown rapidly to more systematically characterize these changes and investigate the extent to which these changes can be reversed with interventions (Chern & Golub, 2019; Deal et al., 2017; Golub et al., 2017; Gurgel et al., 2014; Heywood et al., 2017; Loughrey et al., 2018; Panza et al., 2015; Peracino & Pecorelli, 2016; Yuan et al., 2018; Zheng et al., 2017). Recent research shows that the earliest cognitive changes in individuals with ARHL are seen in cognitive control (Lin et al., 2013; Lin et al., 2011). Cognitive control refers to a broad class of mental operations that allow goal-directed behavior (Botvinick & Braver, 2015; Mackie et al., 2013; Posner & Digirolamo, 1998) and typically involves processes such as cognitive flexibility, inhibitory control, and working memory updating (Diamond, 2013; Miller & Cohen, 2001; Miyake et al., 2000). Cognitive flexibility is one's ability to flexibly switch between different tasks or mental sets of

representations, inhibitory control is the ability to suppress irrelevant information/responses to allow processing of relevant information, and working memory updating is the ability to actively maintain and update incoming information over a short duration of time. Cognitive control is critical for daily functioning, including complex auditory processing. For instance, when engaging in a conversation with multiple speakers in noisy situations (e.g., other conversations in the background), cognitive flexibility allows one to shift listening from one speaker to another while inhibitory control allows suppression of ongoing background conversations. Additionally, every time new information is added to the conversation, working memory is updated with this information in order to keep understanding the conversation. Despite the importance of cognitive control processes in recognition of SiN, which is challenging for individuals with ARHL, a comprehensive understanding of cognitive control changes in this population is lacking.

1.2. Outline of Dissertation

The principal aim of this dissertation was to delineate cognitive control changes in older adults with unaided mild ARHL. For this purpose, three studies were conducted with findings of each informing the goals of the next. The **first study** reviewed the literature on associations between peripheral/central hearing abilities and cognitive control processes of cognitive flexibility, inhibitory control, and working memory updating in individuals with ARHL. The **second study** examined behavioral changes in the less explored processes of cognitive flexibility and inhibitory control in individuals with unaided mild ARHL relative to age- and education-matched NH controls. The **third and final study** examined neurophysiological correlates underlying inhibitory control changes in individuals with unaided mild ARHL relative to age- and education-matched NH controls. As a whole, these studies provide insights into cognitive

control changes observed in individuals with mild ARHL, which have both theoretical and clinical implications.

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Chapter 2. A Narrative Review of Cognitive Control in Age-Related Hearing Loss

Abstract

Recent evidence suggests links between hearing loss and cognitive alterations as well as incident dementia in older adults with age-related hearing loss (ARHL). The earliest cognitive changes have been observed in cognitive control; however, a cohesive account of the links between hearing ability and cognitive control processes in this population is lacking. This review summarizes evidence on (1) the association between peripheral hearing acuity measured using pure-tone audiometry and cognitive control processes and (2) the association between speech-in-noise (SiN) recognition and cognitive control processes in individuals with ARHL. The review focused on behavioral studies of cognitive control linked to cognitive flexibility, inhibitory control, and working memory updating. Overall, working memory updating has been more extensively studied in individuals with ARHL compared to cognitive flexibility and inhibitory control. Additionally, the literature review revealed consistent evidence for associations between peripheral hearing acuity/SiN recognition and both cognitive flexibility and working memory updating involving complex tasks in individuals with ARHL. However, the findings on associations between peripheral hearing acuity/SiN recognition and inhibitory control were mixed. This emerging body of evidence suggests that individuals with ARHL have alterations in certain aspects of cognitive control, making it essential to address these cognitive issues in the context of a comprehensive rehabilitation program.

2.1. Introduction

Age-Related Hearing Loss (ARHL) is a common chronic condition in older adults (Collins, 1997; Cruickshanks et al., 2003; Quaranta et al., 2015) that affects approximately a third of adults between 65-75 years of age and nearly half above the age of 75 years (National Institute on Deafness and Other Communication Disorders, 2018). Decades of research has characterized the impact of ARHL on auditory processing, including detection of sounds, discrimination of frequency and temporal properties of sounds that affect dichotic and binaural processing, recognition and comprehension of speech, and communication and social interactions (Atcherson et al., 2015; Divenyi et al., 2005; Frisina and Walton, 2006; Gates, 2009; Humes, 2013; Humes and Young, 2016; Jerger, 1992; Jerger et al., 1989; Jerger and Jerger, 2014). In the past two decades, evidence of alterations in cognition in individuals with ARHL has come to light (Gordon-Salant and Cole, 2016; Hällgren et al., 2001; Humes, 2002; Lin et al., 2013, 2011a; Lin, 2011; Rönnberg et al., 2011). In fact, large-scale population-based studies have observed an association between hearing loss and cognitive impairment as well as incident dementia in older adults (Deal et al., 2017; Fritze et al., 2016; Granick et al., 1976; Lin et al., 2011b; Mahmoudi et al., 2019; Panza et al., 2015; Tay et al., 2006; Thomson et al., 2017; Valentijn et al., 2005).

The earliest cognitive changes in individuals with ARHL have been noted in cognitive control (Lin et al., 2013; Valentijn et al., 2005), although alterations in multiple other cognitive functions, such as episodic memory, attention, and speed of processing, have also been reported (Burgess et al., 2016; Ellis et al., 2016; Granick et al., 1976; Hällgren et al., 2001; Humes et al., 2006; Rönnberg et al., 2016, 2013; Shahidipour et al., 2013; Stewart and Wingfield, 2010). Cognitive control refers to the ability to coordinate thoughts and actions with internal goals and

suberves higher-order cognitive processes, such as planning and reasoning (Koechlin et al., 2000; Marie, 2009; Miller and Cohen, 2001; Miyake et al., 2000; Rubinstein et al., 2001). Miyake and colleagues (2000) have identified three specific cognitive control processes: cognitive flexibility, inhibitory control, and working memory updating. These cognitive control processes are integral to everyday activities, including speech-in-noise (SiN) recognition abilities (Akeroyd, 2008; CHABA, 1988; Dryden et al., 2017; Neher, 2014; Nuesse et al., 2018). For instance, successful communication in daily listening situations, such as conversations in noisy settings like restaurants, requires listeners to flexibly shift listening between multiple speakers of interest, inhibit irrelevant background noise, and update their working memory every time new information is added to the conversation. However, a cohesive account of the link between hearing ability and cognitive control processes in older adults with ARHL is lacking. This paper will review behavioral evidence on associations between (1) peripheral hearing acuity assessed using pure-tone audiometry and cognitive control performance (see **Table 2.1**) and (2) SiN recognition and cognitive control performance in individuals with ARHL (see **Table 2.2**), focusing on cognitive control processes namely cognitive flexibility, inhibitory control, and working memory updating. The findings of this review will inform clinical practice by identifying cognitive control alterations that should be considered when developing new rehabilitation programs to provide more comprehensive care to address the needs of individuals with ARHL.

2.2. Methods

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. PubMed and PsycINFO search engines were used to search for articles that specifically focused on behavioral performance on measures of cognitive flexibility,

inhibitory control, and working memory updating in older adults with ARHL. Studies were also identified by searching citations.

The following specific inclusion/exclusion criteria were used for selection of studies. Only peer-reviewed articles that consisted of at least one sample/group of individuals with ARHL whose mean age was at least 50 years, had at least mild ARHL, and in whom at least one of the three cognitive control processes, cognitive flexibility, inhibitory control, or working memory updating, was assessed were included. Mild ARHL was quantified on the basis of pure-tone average (PTA) exceeding 25 dB HL or with audiograms depicting bilateral sloping sensorineural hearing loss with at least three pure-tone thresholds (between 0.25 to 8 kHz) exceeding 25 dB HL. Additionally, SiN was quantified on objective tests of SiN recognition. For inclusion, cognitive control had to be examined using standardized neuropsychological assessments or commonly used measures (e.g., substitution, task-switching tests for cognitive flexibility; Stroop, Go/NoGo tasks for inhibitory control; working memory span, *n*-back tasks for updating). Studies that exclusively focused on neural basis of processes linked to cognitive control using techniques such as functional brain imaging, electroencephalography, or pupillometry technique in ARHL, were excluded. Intervention studies that primarily examined the effect of an intervention (e.g., amplification, cognitive training) on cognitive control in older adults with ARHL were also excluded.

2.2.1. Search Strategy for Association between Peripheral Hearing Acuity and Cognitive Control

Studies published in English examining cognitive control in individuals with ARHL were searched up through March 1, 2021 using the following search terms: ("age related" OR older OR elder*) AND ("hearing loss") AND ("executive function" OR "cognitive control" OR cognit* OR inhibition OR "inhibitory control" OR "working memory" OR updating OR

shifting). The search was filtered to include only human studies. The search identified 642 records through the PubMed database and 512 records through PsychInfo, leading to a total of 1,154 records through database searching and an additional 10 studies through other sources, including author searches of references from articles. Of the database searches, 957 remained after removing for duplicates, and of those, 913 were discarded based on the title and/or abstract if they did not assess cognition *and* hearing *in* older adults, which left a total of 44 records. These 44 records and the 10 studies identified through citation searching were sought for retrieval. Of those, 20 studies were further discarded since they did not specifically address cognitive control, did not include quantitative measures of cognitive control, and did not include a study group with mean age > 50 years. A total of 34 studies were eligible and included in the review, of which 11 specifically examined cognitive flexibility, three examined inhibitory control, 12 examined working memory updating, and eight examined more than one cognitive control process (see **Table 2.1** for details of studies, including cognitive control tasks). See **Figure 2.1** for details on methodology.

2.2.2. Search Strategy for Association between SiN Recognition and Cognitive Control

Studies published in English examining SiN recognition and cognitive control in individuals with ARHL were searched up through March 1, 2021 using the following search terms: (older OR elder*) AND ("hearing loss") AND ("executive function" OR "cognitive control" OR cognit* OR inhibition OR "inhibitory control" OR "working memory" OR updating OR shifting OR attention) AND ("speech in noise" OR "speech recognition") NOT children. The search was filtered to only include human studies. The search identified 105 records through the PubMed database and 106 records through PsychInfo, leading to a total of 211 records through database searching and an additional 13 studies through other sources, including author searches

of references from articles. Of the database searches, 181 remained after removing for duplicates, and of those, 154 were discarded based on the title and/or abstract if they did not assess SiN recognition *and* cognition *in* older adults *with* ARHL, which left a total of 27 records. These 27 records and the 13 studies identified through citation searching were sought for retrieval. Of those, 17 studies were further discarded since they did not specifically address cognitive control, did not include standardized/common measures of cognitive control, did not examine association between SiN recognition and cognitive control, included individuals with other hearing loss etiologies or only examined normal hearing individuals, and did not include a study group with mean age > 50 years. A total of 23 studies were eligible and included in the review, of which three examined cognitive flexibility, four examined inhibitory control, and 16 examined working memory updating (see **Table 2.2** for details of studies, including cognitive control tasks). See **Figure 2.2** for details on methodology.

2.3. Relationship between Peripheral Hearing Acuity and Cognitive Control in Individuals with Age-Related Hearing Loss

2.3.1. Cognitive flexibility

Cognitive flexibility is the ability to flexibly allocate resources to process and manage information in a constantly changing environment (Diamond, 2013; Giller and Beste, 2019). For instance, we utilize cognitive flexibility when we switch between listening to different talkers during group conversations at gatherings. Typically, cognitive flexibility is studied using tasks that involve shifting between mental sets of information, or between two or more different tasks (Cañas et al., 2003; Mayr and Keele, 2000; Miyake et al., 2000; Monsell, 1996). In individuals with ARHL, both cross-sectional and longitudinal studies have explored the association between peripheral hearing acuity and cognitive flexibility using visual measures, such as the Digit Symbol Substitution Test (DSST; Lin et al., 2013; Lin, 2011), the Letter Digit Substitution Test

(LDST; Valentijn et al., 2005), the Trail Making Test-B (TMT-B; Harrison Bush et al., 2015; Lin et al., 2011a), the Concept Shifting Task-C (CST-C; Valentijn et al., 2005), and the Attention Switching Task (Jayakody et al., 2018).

The earliest evidence for the link between peripheral hearing acuity and cognitive flexibility in older adults with mild to moderate ARHL came from two cross-sectional studies that used the DSST (Birren et al., 1963; Granick et al., 1976). The DSST is a substitution test in which individuals are asked to code a series of numbers with a set of corresponding symbols in 90 or 120 seconds (Granick et al., 1976; Harrison Bush et al., 2015; Lin et al., 2013; Lin, 2011). The number of correct substitutions within a given time (DSST scores) reflects the accuracy with which one can shift between the mental sets of digits and symbols and is a commonly used metric of cognitive flexibility. Both Birren et al. (1963) and Granick et al. (1976) reported significant negative associations between pure-tone thresholds and DSST scores, demonstrating that individuals with greater severity of hearing loss had lower DSST scores, indicative of poorer cognitive flexibility. Similarly, findings from cross-sectional data obtained from four population-based studies, the National Health and Nutritional Examination Survey (Golub et al., 2020a; Huang et al., 2019; Lin, 2011), the Health, Aging, and Body Composition Study (Lin et al., 2013), the Atherosclerosis Risk in Communities Study (Deal et al., 2015), and the Hispanic Community Health Study (Golub et al., 2020a, 2020b) have shown significant negative associations between pure-tone average (PTA) and DSST scores (see **Table 2.1** for details of pure-tone frequencies used in each of these studies to compute the PTA). More recently, Armstrong et al. (2020) found a negative association between PTA and DSST scores when cross-sectional data from the Baltimore Longitudinal Study of Aging was examined, although the findings did not reach significance. In contrast, other studies on pure-tone hearing ability and

cognitive flexibility measured using substitution tests have not found similar associations in individuals with ARHL. For example, in the longitudinal Maastricht Aging Study, Valentijn et al. (2005) found no correlations between PTA and scores from the LDST, a substitution test similar to DSST but with digit-letter substitutions, in participants with minimal hearing loss at baseline (mean PTA: 16.0 dB HL). Similarly, Harrison Bush et al. (2015), whose study group predominantly included individuals with normal hearing and minimal-to-mild ARHL, found no significant association between PTA and the DSST accuracy score after controlling for health covariates (i.e., diabetes, hypertension, stroke, and heart disease) and sex.

Several factors may explain discrepancies in the findings across studies. Those that found significant associations typically involved participants with a range of hearing loss severity from unaided mild to moderate (Birren et al., 1963; Granick et al., 1976; Lin, 2011) to aided severe hearing loss (Birren et al., 1963; Granick et al., 1976; Lin et al., 2013; Lin, 2011). In contrast, studies that found no association predominantly involved individuals with normal hearing and unaided minimal to mild hearing loss (Harrison Bush et al., 2015; Valentijn et al., 2005).

Whether these findings suggest that a milder degree of hearing loss has less impact on cognitive flexibility needs further examination. Additionally, differences in the measure of hearing acuity, i.e., the thresholds used to compute PTA (see **Table 2.1** for details), may have also contributed to the divergent findings.

In contrast to findings of studies that have used cross-sectional data, findings of most studies that have used longitudinal data demonstrate converging evidence supporting a decline in cognitive flexibility on substitution measures in individuals with ARHL over time and across varying degrees of hearing loss (Lin et al., 2013; Uchida et al., 2016; Valentijn et al., 2005). In particular, PTA at baseline has been associated with worse performance on the LDST (Valentijn

et al., 2005) and the DSST, (Lin et al., 2013) at a six-year follow-up. Furthermore, Lin et al. (2013) reported greater annual rates of decline on the DSST, with an overall 32% greater decline on the DSST at a six-year follow-up in individuals with ARHL as compared to normal hearing controls.

Other commonly used tests to assess cognitive flexibility in individuals with ARHL are the TMT-B (Lezak et al., 2004) and its variation, the CST-C (Van Der Elst et al., 2006). The TMT and CST are trail making tests that consist of “easy” and “difficult” conditions. In the “easy” condition, participants connect numbers and/or letters sequentially (i.e., 1-25; A-Z). In the “difficult” condition, participants are required to alternately connect numbers and letters (i.e., 1-A-2-B-3-C, etc.), known as TMT-B or CST-C conditions. Cognitive flexibility is commonly assessed using completion times on “difficult” conditions. Cross-sectional studies have reported a positive association between measures of peripheral hearing acuity and cognitive flexibility on the TMT-B (Harrison Bush et al., 2015; Huber et al., 2020; Lin et al., 2011a; Ren et al., 2019) and CST-C at baseline (Valentijn et al., 2005). These findings indicate that individuals with greater degrees of hearing loss took longer to switch between mental sets of information compared to those with milder degrees of hearing loss and normal hearing controls (Harrison Bush et al., 2015; Huber et al., 2020; Ren et al., 2019). This trend was also noted by two other studies (Alattar et al., 2020; Armstrong et al., 2020), although the findings of Armstrong et al. (2020) did not reach significance. Additionally, Lin et al. (2011a) found that even a mild degree of hearing loss (equivalent to 25 dB HL) impacts cognitive flexibility leading to a decrease in the TMT-B score that is equivalent to 6.7 years below what is expected for the age range, suggesting a more consistent association between peripheral hearing acuity and cognitive flexibility on the trail making test in individuals with ARHL.

More recently, Jayakody et al. (2018) used the Attention Switching Task to examine cognitive flexibility in individuals with mild to profound ARHL. This task requires participants to execute motor responses that correspond to cue-based stimuli. Based on the cues of “side” or “direction”, participants are asked to push the buttons on the keypad. For example, participants are required to push the “left” button when an arrow either appears on the left-hand side of a computer screen or points to the left. Accuracy scores (percentage of correct responses to the cue-based stimuli) were used as a measure of cognitive flexibility. They did not find a significant association between PTA and accuracy scores. However, no other studies on ARHL have used the Attention Switching measure, hence these findings have not been corroborated.

To summarize, alterations in cognitive flexibility have been consistently observed on measures of TMT-B in cross-sectional studies involving individuals with ARHL. Findings from longitudinal studies offer compelling evidence for a long-term link between ARHL and cognitive flexibility on measures of substitution (DSST and LDST), most notable in those with greater hearing loss severity regardless of hearing aid use. These alterations in cognitive flexibility have been predominantly documented on visual measures suggesting that cognitive changes in individuals with ARHL are not specific to the auditory modality (modality-specific) and are more central.

2.3.2. Inhibitory control

Inhibitory control is the ability to suppress irrelevant information allowing focused processing of relevant information (Hasher et al., 1991; Hasher and Zacks, 1988; Miyake et al., 2000). In the context of auditory processing, we routinely inhibit background noise in our environments to focus on relevant auditory signals (e.g., speech). Cross-sectional (Guerreiro and Van Gerven, 2017; Guglielmi et al., 2019; Harrison Bush et al., 2015; Huber et al., 2020; Janse,

2012; Lin et al., 2011a; Ren et al., 2019; Völter et al., 2017) and longitudinal (Valentijn et al., 2005) studies have examined inhibitory control in individuals with ARHL predominantly using the Stroop task, with the exception of van Knijff et al., 2018, who used the Simon task. Inhibitory control on the Stroop task is primarily measured using the color-word interference condition, in which participants view color names (e.g., red, blue, green) or colored rectangles that contain color names. The task is to name the color of the ink used to write out the color names, not read the color name itself (e.g., name *blue* when the color name GREEN is written in blue ink). Successful performance requires fast and accurate suppression of the habitual response of reading the color name. Completion times and accuracy measures are used as metrics of inhibitory control, with longer completion times and lower accuracy scores reflecting poorer inhibitory control. The Stroop effect, which is the difference in completion time between color-word interference condition and neutral condition (participants simply read color names printed in black ink) is also used to measure inhibitory control, with a higher Stroop effect indicative of poorer inhibitory control.

Some cross-sectional studies have found that higher PTA is associated with longer Stroop completion times (Janse, 2012; Ren et al., 2019) and lower accuracy scores (Lin et al., 2011a) on the color-word interference condition in individuals with mild (Janse, 2012; Lin et al., 2011a) to severe (Lin et al., 2011a) degrees of ARHL. Lin et al. (2011a) found that an increase of 25 dB in hearing thresholds resulted in a decline in the accuracy measure on the Stroop task by an age-equivalent of 6.8 years. In contrast to these findings, other studies with participants with comparable hearing loss severities (mild [Guerreiro and Van Gerven, 2017; Guglielmi et al., 2019]; mild to severe [Harrison Bush et al., 2015; Völter et al., 2017]), have reported no significant association between PTA and Stroop completion time or accuracy measures.

Similarly, no differences were found on Stroop completion time between individuals with severe to profound ARHL and age-matched normal hearing controls (Huber et al., 2020), and no longitudinal declines were observed on the Stroop task (Valentijn et al., 2005).

A study by van Knijff et al. (2018) examined inhibitory control on the adapted Simon task. This task requires participants to make button push responses that are either congruent or incongruent with the side of the stimulus presentation. For example, if a stimulus is presented on the left side of the computer screen, a button press on the left side of the keyboard is required in the congruent condition whereas a button push on the right side of the keyboard is needed in the incongruent condition. The difference in reaction times (time taken to respond to stimulus) for these conditions, known as the Simon effect score, was used as a measure of inhibitory control. They found no association between PTA and the Simon effect score in individuals with mild to moderate ARHL, but these findings need to be corroborated in future studies.

In summary, evidence related to the relationship between hearing acuity measured using pure-tone audiometry and inhibitory control measured using the Stroop task is mixed. To determine whether the changes observed in this population are unique to the Stroop task, future studies should examine inhibitory control using other classic tasks such as the Go/NoGo and the Stop-Signal tasks. Factors such as duration of hearing loss, amplification use, and consistency of use, should also be considered. Additionally, the association between hearing acuity measures using pure-tone audiometry and inhibitory control has been predominantly established on visual tasks. Future studies that examine inhibitory control using auditory paradigms will be critical to advance this body of research.

2.3.3. *Working memory*

Working memory is defined as a limited capacity cognitive system (Baddeley, 1983; Daneman and Carpenter, 1980; Engle and Kane, 2003) that is responsible for active maintenance and updating of information over brief periods of time (Ecker et al., 2010; Miyake and Shah, 1999; Nyberg and Eriksson, 2015). Maintenance refers to the process in which information is held over a short interval of time, whereas updating refers to the process of monitoring incoming information and revising older information that is no longer relevant with new, relevant information (Miyake and Shah, 1999; Morris and Jones, 1990). Importantly, the core distinction between maintenance and updating functions is that the latter involves active manipulation, or processing, of the contents in working memory as opposed to brief passive retention of items (Kessler and Oberauer, 2014; Miyake and Shah, 1999).

Numerous studies have examined working memory in older adults with ARHL (Bruce et al., 2019; Cervera et al., 2009; Guerreiro and Van Gerven, 2017; Hällgren et al. 2001; Jayakody et al., 2018; Na et al., 2017; Nagaraj, 2017; Van Rooij & Plom., 1989; Völter et al., 2017; Zekveld et al., 2007). The updating function of working memory, in particular, is considered a crucial subcomponent of cognitive control (Baddeley, 1983; Baddeley et al., 2018; Braver et al., 2001; Engle and Kane, 2003). Working memory updating has been examined using both auditory and visual updating tasks in individuals with ARHL. Studies in the auditory modality have used simple updating tasks, such as digit ordering (Cervera et al., 2009) and backward digit span (Na et al., 2017; Van Rooij & Plom., 1989), to more complex tasks such as listening span (Nagaraj, 2017) and *n*-back tasks (Guerreiro and Van Gerven, 2017; Nixon et al., 2019). Visual modality studies have used reading span (Foo et al., 2008; Hällgren et al. 2001; Lunner, 2003; Nagaraj, 2017; Souza et al., 2015), operation span (Völter et al., 2017), *n*-back (Bruce et al.,

2019; Guerreiro and Van Gerven, 2017; Nixon et al., 2019; Völter et al., 2017), Cambridge Neuropsychological Test Automated Battery (CANTAB) spatial working memory task (Jayakody et al., 2018; Zekveld et al., 2007), and the letter monitoring task (Foo et al., 2008). Accuracy score or span length, which refers to the longest list of items recalled correctly, is calculated to measure updating, with higher scores reflecting better ability to dynamically manipulate and update information.

Evidence supporting the association between peripheral hearing acuity and updating ability tested using auditory modality tasks is mixed. For instance, Cervera et al. (2009) reported a significant negative association between PTA and accuracy on the digit-ordering task. Whereas, two studies reported no association between PTA and accuracy on the backward digit span task (Na et al., 2017; Van Rooij & Plom, 1989). Given that all studies included older adults whose hearing ranged from normal to moderate hearing loss, the divergent findings may have resulted from differences in the complexity of information manipulation across these two studies. The backward digit span task requires participants to recall the presented digits in the reverse order (e.g., recall the number sequence “2, 8, 5, 4” as “4, 5, 8, 2”), whereas the relatively complex digit-ordering task requires digit recall in ascending order (e.g., recall the number sequence “2, 8, 5, 4” as “2, 4, 5, 8”), thereby requiring more information manipulation in terms of reorganizing the digits in one’s working memory. Similarly, in older adults with normal hearing and mild ARHL, Bruce et al. (2017) found no significant association between PTA and the auditory 1-back task, with similar findings reported by Nixon et al. (2019) on the visual 1-back task. Whereas, Guerreiro and Van Gerven (2017) found a significant negative association between PTA and accuracy on a relatively complex version of the auditory *n*-back task, i.e., 2-back task. In the *n*-back task, participants are presented with a series of stimuli, and for each

stimulus, they are to judge if it matches a stimulus presented n trials before. Thus, the 2-back task requires greater encoding and storage of each stimulus sequence in one's working memory and greater continuous updating of the incoming stimulus relative to the 1-back task, which may have contributed to the divergent findings. Collectively, the findings indicate that complexity of information manipulation in one's working memory influences the relationship between peripheral hearing acuity and updating in individuals with ARHL.

In addition to task complexity, differences in presentation levels of auditory stimuli across studies may have contributed to divergent findings. For instance, Bruce et al. (2019) presented 1-back task stimuli at 50 dB above each participant's average pure-tone thresholds and found no significant association between hearing acuity and updating. This was similar to Nagaraj (2017) who, after controlling for peripheral hearing deficits of each participant by increasing sound gain using real-time signal processors, found no significant association between PTA and accuracy on the listening span task, which requires participants to recall a series of digits while simultaneously performing word discrimination. In contrast, studies that did not make adjustments based on hearing deficits have reported significant negative associations between PTA and accuracy on updating tasks (Cervera et al., 2009; Guerreiro and Van Gerven, 2017; Na et al., 2017). Overall, these findings indicate that studies that did not account for individual hearing deficits may have overestimated auditory working memory deficits.

Studies that have assessed working memory using the visual modality tasks, such as the CANTAB spatial working memory task and the reading span task, have also yielded mixed findings. For instance, Jayakody et al. (2018) found that higher PTA was associated with higher updating errors and high working memory strategy score (poorer updating) on the spatial working memory task, which requires participants to maintain and regularly update the spatial

location of visual stimuli on a computer screen. In contrast, Zekveld et al. (2007) found that higher PTA was associated with a low strategy score (better updating) on the same task. Some have reported a negative association between PTA and reading span accuracy scores (Foo et al., 2008; Lunner, 2003), with a similar pattern noted with operation span task (Volter et al., 2017 [participants simultaneously recall increasing numbers of digits/letters and judge accurateness of a visually presented arithmetic equation]); whereas, others have found no significant associations (Hällgren et al. 2001; Nagaraj, 2017; Souza et al., 2015) using the same measures. One reason for the discrepancy between findings could be related to a difference in the range of severity of participants' hearing impairments, with studies reporting working memory deficits when subject pools included individuals with mild to profound (Jayakody et al., 2018) and mild to moderately severe loss (Lunner, 2003), compared to when only individuals with mild hearing loss (Zekveld et al., 2007) were included.

Another reason for the divergent findings could be due to task differences, particularly in the subset of studies that used the reading span task. Studies that have reported significant associations (Foo et al., 2008; Lunner, 2003) have used the traditional reading span task, which requires participants to make true/false judgments about each sentence (e.g., "The sick boy had to stay home from school because he had a phone"), following which they are asked to recall either the first or last word from each sentence in a serial order. In contrast, Nagaraj (2017), who reported non-significant findings, used a modified version of the reading span task wherein participants with unaided hearing loss were required to recall letters that were presented after each of the reading span sentences, and these letters were unrelated to the sentences presented. Furthermore, it is interesting to note that while Foo et al. (2008) reported a significant negative association between PTA and accuracy on the reading span task, they found no significant

associations with visual letter monitoring tasks. This task requires the identification of lexical items of the Consonant-Vowel-Consonant (CVC) form in a continuous stream of presented letters (Foo et al., 2008), and in contrast to the reading span task, requires a lesser amount of information manipulation. Collectively, findings from these studies indicate that the association between peripheral hearing acuity and working memory measured using visual modality is influenced by the severity of hearing impairment, task differences, and task complexity, the latter of which was also seen in studies that used auditory working memory tasks.

In summary, while the overall findings of studies that have examined working memory updating in individuals with ARHL seem equivocal, deficits in updating have been most consistently reported by studies that have used more complex auditory (Cervera et al., 2009; Guerreiro and Van Gerven, 2017) and visual (Foo et al., 2008; Lunner, 2003) updating tasks/conditions and in individuals with different degrees of hearing loss. However, it is important to note that deficits noted in studies that used auditory measures of working memory without adjusting for reduced audibility may have overestimated the deficits.

2.4. Relationship between SiN Recognition and Cognitive Control in Individuals with Age-Related Hearing Loss

A primary concern of individuals with ARHL is difficulty in recognition of speech in adverse listening conditions, such as noisy and reverberant environments (Chmiel and Jerger, 1996; Davis et al., 2016; Divenyi et al., 2005; Frisina and Frisina, 1997; Gates and Mills, 2005; Jerger, 1992; Jerger et al., 1995) which are routinely encountered in daily life. Studies suggest that speech recognition difficulties persist in these environments despite using state-of-art amplification devices (Bentler, 2005; Kochkin, 2007). Growing evidence suggests that in addition to auditory dysfunction, alterations in cognition contribute to speech recognition deficits in this population (Akeroyd, 2008; CHABA, 1988; Dryden et al., 2017; Foo et al., 2008; Lunner,

2003). The following section will review behavioral evidence on the relationship between SiN recognition and cognitive control processes of cognitive flexibility, inhibitory control, and working memory updating in individuals with ARHL.

2.4.1. SiN Recognition and Cognitive Flexibility

The link between SiN recognition and cognitive flexibility in ARHL has mostly received attention in the past decade (Ellis et al., 2016; Ellis and Munro, 2015; Woods et al., 2013). Studies have examined SiN recognition using word recognition in isolation (Ellis et al., 2016) and in sentences (Ellis and Munro, 2015) in the presence of background noise; and have examined cognitive flexibility using TMT-B (Ellis et al., 2016; Ellis and Munro, 2015).

A consistent association has been observed between SiN recognition and cognitive flexibility in individuals with ARHL. Ellis and Munro (2015) found that lower accuracy for word recognition in sentences against multi-talker babble was associated with longer completion times on the TMT-B in individuals with moderate to severe high-frequency hearing loss. In another study, Ellis et al. (2016) found that higher signal-to-noise ratio (SNR) levels, at which individuals with hearing loss obtained 50% correct recognition of words presented against speech-shaped background noise, was also associated with longer TMT-B completion times. Woods et al. (2013) examined SiN recognition using multiple talkers and cognitive flexibility using TMT-B in individuals with mild to profound ARHL. They used the Nonsense-Syllable Response Measure (NSRM) sentences, which take the generic form of “READY NAME mark SYLLABLE now”, in which the NAME refers to names of specific talkers, and participants are required to mark the syllables that are spoken by a specific talker and ignore those spoken by other competing talkers. The NSRM sentences were presented with different noise maskers including a single talker, a single talker plus speech-shaped background noise, a single talker

plus background noise, and four talkers speaking NSRM sentences. They found that a lower proportion of correct syllable recognition in the presence of four talkers speaking NSRM sentences was associated with longer TMT-B completion time in older adults with ARHL. These findings are not surprising given that successful recognition of speech in situations with multiple talkers requires listeners to switch between constantly changing talkers, drawing heavily on cognitive flexibility.

In summary, worse SiN recognition is associated with poorer cognitive flexibility. This association has also been demonstrated in individuals with different degrees of hearing loss, from mild (Ellis et al., 2016; Woods et al., 2013) to more severe loss (Ellis and Munro, 2015; Woods et al., 2013). Furthermore, consistent associations between measures of SiN recognition in both simple (Ellis et al., 2016) and complex types of background noise, such as multi-talker babble (Ellis and Munro, 2015), and cognitive flexibility have also been observed.

2.4.2. SiN Recognition and Inhibitory control

A handful of studies have examined the association between SiN recognition and inhibitory control in ARHL (Janse, 2012; Knight and Heinrich, 2017, 2019; van Knijff et al., 2018). These studies have examined SiN recognition for phonemes in the context of sentences (Janse, 2012; van Knijff et al., 2018) and word recognition in isolation and at sentence level contexts (Knight and Heinrich, 2017, 2019), and inhibitory control using visual (Janse, 2012; Knight and Heinrich, 2017, 2019) and auditory Stroop tasks (Knight and Heinrich, 2017), and a visual adapted Simon task (van Knijff et al., 2018).

A consistent association has been observed between phoneme recognition in noise and inhibitory control in individuals with ARHL. Janse (2012) found that a lower hit rate of correct phoneme identification in sentences (number of phonemes correctly recognized in relation to the

total number of phonemes in the sentence) in the presence of competing speech was associated with a higher visual Stroop effect. Similarly, van Knijff et al. (2012) reported that lower accuracy of correct phoneme recognition in sentences with a background noise spectrum resembling the long-term average speech spectrum was associated with higher scores on the visual adapted Simon task (worse performance). Both studies included individuals with mild ARHL, and their findings suggest that inhibitory changes in this population are related to deficits in phoneme recognition in background noise. It should be noted that Janse (2012) reported this association only when complex noise, such as competing-talker sentences that matched the duration of the speech sentences, was used as opposed to non-competing talker sentences, suggesting that the relationship between phoneme recognition and inhibitory control is influenced by the type of background noise.

The findings of an association between word recognition and inhibitory control are rather mixed. Knight and Heinrich (2017) found that lower accuracy of isolated word recognition in speech modulated background noise was associated with a higher visual Stroop effect in individuals with mild ARHL. They did not observe a significant association between the accuracy of word recognition in sentences and the visual Stroop effect. However, in their subsequent study with the same group of participants and test measures, they found that educational attainment modulated the significant association between word recognition (in isolation and sentence contexts) in speech modulated noise and visual Stroop effect (Knight and Heinrich, 2019). Specifically, lower accuracy of word recognition in those with fewer years of formal education (lowest education included was 10 years) was associated with a higher visual Stroop effect. Considering that education influences cognitive functioning (Evans et al., 1997; Karp et al., 2004; Stern et al., 1994), it is not surprising that educational attainment influenced

the relationship between word recognition and inhibitory control. In addition to the visual Stroop task, Knight and Heinrich (2017) examined inhibitory control using an auditory Stroop task. Participants listened to male and female talkers say one of the three words “mother”, “father” or “person” at 30 dB suprathreshold levels. Participants were asked to judge whether the word spoken matched the sex of the speaker and make a corresponding button push response. The reaction time of neutral trials (e.g., the word “person” spoken by a male talker) was subtracted from the reaction time of incongruent trials (e.g., the word “mother” spoken by a male talker) to estimate a measure of inhibitory control. They found that poorer recognition of isolated words in the presence of modulated noise was associated with better performance on the auditory Stroop task, whereas no associations were seen with word recognition in sentences.

In summary, emerging evidence suggests a consistent association between phoneme recognition in complex background noise and inhibitory control in individuals with ARHL. However, the association between word recognition and inhibitory control seems to vary depending on whether it involves isolated word recognition or word recognition in sentence context, educational attainment, and the modality of testing. The few studies that have examined SiN recognition and inhibitory control have predominantly included individuals with mild ARHL, and the extent to which these associations apply to individuals with greater hearing loss severities needs further examination.

2.4.3. SiN Recognition and Working Memory

The relationship between SiN recognition and working memory has been extensively studied in ARHL (Arehart et al., 2013; Borch Petersen et al., 2016; Cervera et al., 2009; Foo et al., 2008; Heinrich et al., 2015; Lunner, 2003; Lunner and Sundewall-Thorén, 2008; Murphy et al., 2018; Nagaraj, 2017; Ng et al., 2013; Rudner et al., 2012; Souza and Arehart, 2015; Souza &

Sirow, 2014; Souza et al., 2015). In fact, the Ease of Language Understanding (ELU; Rönnberg et al., 2013) model offers a frame of reference for the role of working memory in language understanding, including recognition of speech in difficult situations, such as background noise, in individuals with hearing loss. SiN recognition has been commonly assessed at the level of word recognition in isolation or sentences. The studies of working memory in ARHL, in particular updating, have used visual tasks of reading span (Lunner, 2003; Souza and Arehart, 2015), letter monitoring (Heinrich et al., 2015; Lunner and Sundewall-Thorén, 2008; Rudner et al., 2012), backward digit span (Moore et al., 2014), and *n*-back tasks (Nagaraj, 2017), with the exception of Nagaraj (2017) who also used an auditory listening span task.

Evidence on the relationship between isolated word recognition in noise and working memory updating is mixed. For instance, Heinrich et al. (2015) found a negative association between 50% correct word recognition in the presence of speech-shaped background noise and accuracy on the visual backward digit span task. However, no significant associations were observed between isolated word recognition in modulated noise and updating on the visual letter monitoring task (Heinrich et al., 2015), as well with word recognition in white noise on visual backward digit span task (Murphy et al., 2018). Differences in the background noise used across studies may have contributed to the divergent findings. The modulated and white noise used by Heinrich et al. (2015) and Murphy et al. (2018) are relatively simpler compared to the more complex speech-shaped noise suggesting that complexity of background noise may play a role in link between updating and isolated word recognition in noise.

The evidence supporting the relationship between word recognition in noise in the context of sentences and working memory updating is also mixed. Most studies have found that higher SNR levels to achieve 40% (Lunner, 2003), 50% (Borch Petersen et al., 2016; Rudner et

al., 2012; Souza and Arehart, 2015; Souza & Sirow, 2014; Vermeire et al., 2019), and 80% (Foo et al., 2008; Lunner and Sundewall-Thorén, 2008; Rudner et al., 2012) correct word-in-sentence/sentence recognition are associated with lower accuracy scores on visual working memory updating tasks, such as reading span and its variation (Borch Petersen et al., 2016; Lunner, 2003; Souza & Sirow, 2014; Souza et al., 2015) and the letter monitoring tasks (Lunner and Sundewall-Thorén, 2008; Rudner et al., 2012). In a similar vein, lower accuracy of correct word-in-sentence/sentence recognition in presence of babble noise was associated with lower accuracy scores on the visual reading span task (Arehart et al., 2013; Ng et al., 2013). These findings were observed when low-context sentences, where context does not allow prediction of upcoming words (Arehart et al., 2013; Borch Petersen et al., 2016; Lunner, 2003; Lunner and Sundewall-Thorén, 2008; Rudner et al., 2012; Souza and Arehart, 2015; Souza & Sirow, 2014), were used in the presence of both simple steady-state background noise (Rudner et al., 2012) and complex noise, including modulated and unmodulated noise (Foo et al., 2008; Lunner and Sundewall-Thorén, 2008), as well as competing speech (Foo et al., 2008; Lunner and Sundewall-Thorén, 2008; Souza and Arehart, 2015). These findings suggest that worse SiN recognition was associated with poorer updating of information and this relationship has been demonstrated across hearing loss severities ranging from mild to moderate (Foo et al., 2008; Lunner and Sundewall-Thorén, 2008; Rudner et al., 2012) and moderate to moderately severe loss (Lunner, 2003; Ng et al., 2013). On the contrary, some studies have reported no significant associations between SiN recognition and accuracy on the visual reading span task (Foo et al., 2008; Nagaraj, 2017; Shehorn et al., 2018; Souza et al., 2015), visual *n*-back task (Nagaraj, 2017), digit ordering task (Cervera et al., 2009), and the listening span task (Nagaraj, 2017), in older adults with mild to moderate (Cervera et al., 2009; Foo et al., 2008; Nagaraj, 2017; Shehorn et al., 2018) and

moderately severe hearing loss (Souza et al., 2015). It is important to note that studies that found no significant associations included data that combined recognition scores for both high-and low-context sentences (Nagaraj, 2017; Shehorn et al., 2018), whereas studies that found significant association included data from low-context sentences, suggesting that differences in SiN measures also could have led to the divergence in findings.

To summarize, although the results of studies on the link between SiN recognition and working memory updating are mostly incongruous, the most consistent association has been observed between recognition of words in low-context sentences in background noise and complex working memory updating tasks. So far, the association between SiN recognition and updating has been predominantly examined using visual working memory tasks, except for two studies that used an auditory working memory task (Murphy et al., 2018; Nagaraj, 2017).

2.5. Summary and Conclusion

This paper reviewed behavioral evidence on associations between peripheral hearing acuity assessed using pure-tone audiometry and SiN recognition, and cognitive control, namely cognitive flexibility, inhibitory control, and working memory updating, in individuals with ARHL. Overall, working memory updating has been most extensively examined relative to cognitive flexibility and inhibitory control. The most consistent evidence was observed for associations between peripheral hearing acuity/SiN recognition and cognitive flexibility. Findings from these studies suggest that individuals with higher PTA and lower SiN scores (word recognition in isolation and sentence context) have more pronounced changes in cognitive flexibility. Furthermore, a longitudinal decline in cognitive flexibility was found in this population, indicating long-term alterations. Alterations in cognitive flexibility noted in individuals with ARHL are above and beyond what is typically observed as part of normal

cognitive aging. Given that cognitive flexibility allows individuals to navigate continuously changing environments, both auditory and visual, one might surmise that such alterations in cognitive flexibility would further exacerbate the functional handicap experienced by these older adults due to their peripheral hearing dysfunction. These findings highlight the importance of developing effective approaches (e.g., cognitive training programs; compensatory strategies) that address these alterations in cognitive flexibility to minimize the functional barriers and integrate them into routine hearing rehabilitation, as has been recently suggested by others (Henshaw and Ferguson, 2013; Lawrence et al., 2018).

Interestingly, of the three cognitive control processes, inhibitory control has been narrowly sampled using mostly the Stroop task. The findings on the association between PTA/SiN recognition and inhibitory control have been inconclusive when examined in auditory and visual modalities. From this body of work, it is challenging to draw any general interpretations that are not task-specific. Future studies should use a variety of tasks (e.g., Go/NoGo tasks) that have been successfully utilized to examine inhibitory control in healthy cognitive aging as well as clinical populations (e.g., mild cognitive impairment, Parkinson's disease [Falkenstein et al., 1999; Mudar et al., 2016, 2015; Nguyen et al., 2017; Yang et al., 2018]). Such systematic sampling will allow for better characterization of inhibitory control in individuals with ARHL.

The most in-depth examination of the association between hearing ability and cognitive control comes from cross-sectional studies on working memory. Broadly speaking, higher PTA and lower SiN scores for word recognition in sentences have been associated with worse performance on complex working memory measures. Whether these alterations, observed cross-sectionally, worsen over time remains unknown and needs to be studied. Accumulating evidence

indicates an important role of working memory updating in complex language processing (Mishra et al., 2014; Rönnberg et al., 2011, 2016). For instance, in conversational settings, updating allows listeners to continually replace information stored in working memory with new incoming information, facilitating successful communication. Alterations in updating of information in older adults with ARHL could partly impact conversational challenges reported by these individuals, such as carrying out conversations with someone during crowded meetings, in a bus/car, or on a busy street, following conversations between people during dinner, and understanding a shop assistant in a crowded store (Hallberg et al., 2008; Kramer et al., 1998). Considering that such situations are encountered routinely, addressing working memory alterations is critical to improving older adults' hearing health.

One of the gaps observed during this literature review is that none of the studies have concurrently examined the three cognitive control processes discussed in this paper (cognitive flexibility, inhibitory control, and working memory updating). Such examination is necessary to extend the body of work on cognitive control changes in this population. Furthermore, a better understanding of these alterations will only be possible if these functions are assessed using a variety of tasks involving auditory and visual modalities to parse out modality-specific and central changes in cognitive control.

Evidence of cognitive control alteration and its association with hearing abilities/functioning is in accordance with theoretical propositions like the information-degradation (CHABA, 1988; Schneider and Pichora-Fuller, 2000) and sensory-deprivation (Lin et al., 2013; Lindenberger and Baltes, 1994; Schneider and Pichora-Fuller, 2000) hypotheses, which have long postulated the link between hearing loss and cognition. Broadly, these hypotheses suggest that hearing loss leads to increased engagement of cognitive resources to

support auditory functions (CHABA, 1988; Schneider and Pichora-Fuller, 2000), at the cost of impacting other cognitive abilities (Lindenberger and Baltes, 1994; Schneider and Pichora-Fuller, 2000). It is not surprising that top-down cognitive control processes appear to be compromised, consistent with these speculations. Additionally, in accordance with the common-cause hypothesis (Baltes & Lindenberger, 1997; Wayne & Johnsrude, 2015), it could be that the common factor of aging-related widespread neurodegeneration causes deficits in both ARHL and cognitive control, and thus links the two. Considering that studies have reported long-term declines in cognitive flexibility in older adults with hearing loss, as well as a higher risk of incident dementia in relation to normal hearing counterparts (Lin et al., 2011b), understanding cognitive control alterations in this population has become more crucial than ever before. Knowledge of cognitive control changes is especially important from the clinical standpoint to develop more integrated rehabilitation approaches that address not only the auditory challenges with amplification, auditory training, and counseling, but also to directly address the cognitive challenges. Complementing traditional auditory rehabilitation approaches with cognitive training interventions that target cognitive control abilities might help address speech-recognition challenges, as well as other functional handicaps, faced by individuals with ARHL and lead to improved outcomes. Furthermore, with evidence of long-standing declines in cognitive flexibility, such hybrid intervention approaches may help alleviate cognitive decline in older adults with ARHL as they age.

2.6. Tables and Figures

Table 2.1.

Summary of Studies on the Association between Peripheral Hearing Acuity Measured using Pure-Tone Audiometry & Cognitive Control in Individuals with ARHL

Study	Study type	Participant demographics	Audiological profile	Cognitive control task(s)	Findings
<i>Cognitive flexibility</i>					
Birren et al. (1963)	Cross-sectional	$n = 48$, age = 71.5 (4.8)	Pure-tone thresholds obtained at 0.125, 0.25, 0.5, 1, 2, 3, 4, 6, & 8 kHz that ranged from mild to moderate loss ^a	DSST Modality: visual	Significant negative association
Granick et al. (1976)	Cross-sectional	$n = 38$, age = 75.9 (5.3)	Pure-tone thresholds obtained at 0.125, 0.25, 0.5, 1, 2, 3, 4, 6, & 8 kHz that ranged from mild to moderate loss ^a	DSST Modality: visual	Significant negative association
Lin (2011)	Cross-sectional data from the National Health and Nutritional Examination Survey Study	age = 64.1 (2.9) <u>NH</u> : $n = 433$ <u>HL</u> : mild: $n = 128$, moderate: $n = 43$, severe: $n = 1$	NH to severe loss; mean better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided & aided participants	DSST Modality: visual	Significant negative association ^b
Lin et al. (2011a)	Cross-sectional data of the Baltimore Longitudinal Study of Aging	age = 71.0 (7.2) <u>NH</u> : $n = 205$ <u>HL</u> : mild: $n = 99$, moderate: $n = 40$, severe: $n = 3$	NH to severe loss; mean better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided & aided participants	TMT-B Modality: visual	Significant negative association ^b
Harrison Bush et al. (2015)	Cross-sectional	age = 73.5 (6.0) <u>NH</u> : $n = 595$ <u>HL</u> : $n = 299$	NH to severe loss; mean better ear PTA computed using thresholds at 0.5, 1, & 2 kHz; unaided participants	DSST, TMT-B Modality: visual	Significant positive association: PTA & TMT-B

Table 2.1. (cont.)

Deal et al. (2015)	Cross-sectional data from the longitudinal Atherosclerosis Risk in Communities Study	<u>NH</u> : $n = 73$, age = 53.8 (4.0) <u>HL</u> : mild: $n = 95$, age = 56.4 (4.9), moderate/severe: $n = 85$, age = 59.1 (5.4)	NH & mild to severe loss; PTA computed using thresholds at 1, 2, & 4 kHz; unaided & aided participants at baseline	DSST Modality: visual	Significant positive association
Jayakody et al. (2017)	Cross-sectional	<u>NH</u> : $n = 47$, age = 58.0 (9.2) <u>HL</u> : mild to moderate: $n = 51$, age = 67.5 (10.3), moderately severe to profound: $n = 21$, age = 67.4 (12.9)	NH to profound loss; better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided participants	Attention Switching Task Modality: visual	No significant association
Ren et al. (2019)	Cross-sectional	<u>NH</u> : $n = 35$, age = 65.1 (3.3) <u>HL</u> : $n = 45$, age = 66.3 (4.4)	NH to mild loss; mean better ear PTA computed using thresholds at 0.5, 1, & 2 kHz; unaided participants	TMT-B Modality: visual	Significant positive association
Völter et al. (2017)	Cross-sectional	age = 65.8 (8.9) <u>NH</u> : $n = 80$ <u>HL</u> : severe to profound: $n = 40$	NH & severe-to-profound loss; better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; aided participants	TMT-B Modality: visual	No significant association
Golub et al. (2020a)	Cross-sectional data from the Hispanic Community Health Study and the National Health and Nutrition Examination Study	age = 59.4 (6.1) <u>NH</u> : $n = \text{not specified}$ <u>HL</u> : $n = 1221$	NH & mild to profound HL; better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; aided participants	DSST Modality: visual	Significant negative association
Huang et al. (2019)	Cross-sectional data from the National Health and Nutrition Examination Study	age = 63.89 (0.19) <u>NH</u> : $n = 511$ <u>HL</u> : mild: $n = 105$, $\geq$ moderate to severe: $n = 39$ age = 81.0 (6.4)	NH, mild & >moderate loss; mean better ear PTA computed using thresholds 0.5, 1, 2, & 4 kHz; unaided & aided participants	DSST	Significant negative association ^b (in male group)

Table 2.1. (cont.)

Golub et al. (2020b)	Cross-sectional data from the Hispanic Community Health Study	age = 58.4 (6.2) <u>NH</u> : $n = 4347$ <u>HL</u> : mild: $n = 746$, moderate: $n = 136$, $\geq$ moderately-severe: $n = 48$	NH, mild, moderate, and $\geq$ moderately-severe HL; better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided & aided participants	DSST	Significant negative association ^b
Huber et al. (2020)	Cross-sectional	<u>NH</u> : $n = 30$, age = 68.3 (4.8) <u>HL</u> : $n = 30$, age = 70.6 (4.6)	NH & severe-to-profound loss; mean better ear PTA computed using thresholds 0.5, 1, 2, & 4 kHz; unaided & aided participants	TMT-B Modality: visual	No significant association
Valentijn et al. (2005)	Longitudinal dataset from the Maastricht Aging Study	<u>Details at baseline</u> $N = 418$, age = 65.9 (6.7)	Minimal & mild loss; mean better ear PTA at baseline & 6-year follow-up computed using thresholds at 1, 2, & 4 kHz; unaided & aided participants	CST-C, LDST Modality: visual	Significant negative association: PTA at baseline & LDST at 6-year follow-up
Lin et al. (2013)	Longitudinal dataset of the Health Aging & Body composition study	<u>Details at baseline</u> <u>NH</u> : $n = 822$, age = 76.8 (2.7) <u>HL</u> : age = 77.9 (2.8), mild: $n = 762$, moderate: $n = 386$, severe: $n = 14$	NH to severe loss; mean better ear PTA at baseline & 6-year follow-up computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided & aided participants	DSST Modality: visual	Significant negative association at baseline & 6-year follow-up ^b
Uchida et al. (2016)	Longitudinal dataset of the Longitudinal Study of Aging at the National Institute for Longevity Sciences	<u>Details at baseline</u> <u>NH</u> : $n = 698$, age = 67.2 (5.2) <u>HL</u> : age = 71.2 (5.0)	NH to mild loss; mean better ear PTA at baseline & 12-year follow-up computed using thresholds at 0.5, 1, 2, & 4 kHz; amplification use not specified	DSST Modality: visual	Significant negative association at 12-year follow-up
Armstrong et al. (2020)	Longitudinal dataset of the Baltimore Longitudinal Study of Aging	<u>Details at baseline</u> $n = 313$, age = 73.9 (8.0)	Mild HL; mean PTA at baseline & 2-year follow-up computed using thresholds at 0.5, 1, 2, & 4 kHz in better ear; unaided & aided participants	DSST, TMT-B Modality: visual	No significant association

Table 2.1. (cont.)

Alattar et al. (2020)	Longitudinal dataset of the Rancho Bernardo Study of Healthy Aging	<u>Details at baseline</u> <u>NH</u> : $n = 388$, age = 67.2 (8.6) <u>HL</u> : mild: $n = 580$, age = 75.1 (8.0); moderate to severe: $n = 196$, age = 81.0 (6.4)	NH to moderate-severe HL; mean PTA at baseline & follow-up (NH: ~10 years, mild: ~ 7 years; moderate: ~ 4 years) computed using thresholds at 0.5, 1, 2, & 4 kHz in better ear; unaided participants	TMT-B Modality: visual	Significant positive association
<i>Inhibitory control</i>					
Lin et al. (2011a)	Cross-sectional data of the Baltimore Longitudinal Study of Aging	age=71.0 (7.2) <u>NH</u> : $n = 205$ <u>HL</u> : mild: $n = 99$, moderate: $n = 40$, severe: $n = 3$	NH to severe loss; mean better ear PTA computed using thresholds 0.5, 1, 2, & 4 kHz; unaided & aided participants	Stroop Modality: visual	Significant negative association ^c
Janse (2012)	Cross-sectional	$n = 39$, age = 72.0 (4.9)	Mild loss; mean PTA computed using thresholds at 1, 2, & 4 kHz; unaided participants	Stroop Modality: visual	Significant positive association
Harrison Bush et al. (2016)	Cross-sectional	age = 73.5 (6.0) <u>NH</u> : $n = 595$ <u>HL</u> : $n = 299$	NH to severe loss; mean better ear PTA computed using thresholds at 0.5, 1, & 2 kHz; unaided participants	Stroop Modality: visual	No significant association
Guerreiro & Van Gerven (2017)	Cross-sectional	<u>NH</u> Young: $n = 54$, age = 22.0 (2.2) Older: $n = 22$, age = 66.1 (5.2) <u>HL</u> Older: $n = 22$, age = 66.7 (4.8)	NH to mild loss; mean better ear PTA computed using thresholds 0.5, 1, 2, & 4 kHz; unaided participants	Stroop Modality: visual	No significant association
Völter et al. (2017)	Cross-sectional	age = 65.8 (8.9) <u>NH</u> : $n = 80$ <u>HL</u> : severe to profound: $n = 40$	NH & severe-to-profound loss; better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; aided participants	Flanker Modality: visual	No significant association

Table 2.1. (cont.)

van Knijff, et al. (2018)	Cross-sectional	<u>NH</u> : Young: $n = 25$, age = 47.0 (9.6) Older: $n = 9$, age = 70.0 (5.4) <u>HL</u> : Older: $n = 17$, age = 74.0 (6.1)	NH to mild loss; mean better ear PTA computed using thresholds 0.5, 1, 2, & 4 kHz; unaided & aided participants	Adapted Simon task Modality: visual	No significant association
Ren et al. (2019)	Cross-sectional	<u>NH</u> : $n = 35$, age = 65.1 (3.3) <u>HL</u> : $n = 45$, age = 66.3 (4.4)	NH & mild loss; Mean better ear PTA computed using thresholds at 0.5, 1, & 2 kHz; unaided participants	Stroop Modality: visual	Significant positive association
Guglielmi et al. (2019)	Cross-sectional	<u>NH</u> : $n = 40$, age = 73.6 (5.6) <u>HL</u> : mild: $n = 23$, age = 73.5 (5.6); moderate: $n = 19$, age = 76.3 (3.7)	NH, mild and moderate HL; Mean better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided participants	Stroop Modality: visual	No significant association
Huber et al. (2020)	Cross-sectional	<u>NH</u> : $n = 30$, age = 68.3 (4.8) <u>HL</u> : $n = 30$, age = 70.6 (4.6)	NH & severe-to-profound loss; mean better ear PTA computed using thresholds 0.5, 1, 2, & 4 kHz; unaided & aided participants	Stroop Modality: visual	No significant association
Valentijn et al. (2005)	Longitudinal dataset from the Maastricht Aging Study	<u>Details at baseline</u> $n = 418$, age = 65.9 (6.7)	Minimal & mild loss; mean better ear PTA at baseline & 6-year follow-up computed using thresholds at 1, 2, & 4 kHz; unaided & aided participants	Stroop Modality: visual	No significant association
<i>Working memory updating</i>					
Van Rooij & Plom (1989)	Cross-sectional	$n = 72$, age = 73.9 (7.8)	Pure-tone thresholds obtained at 0.125, 0.25, 0.5, 1, 2, 3, 4, 6, & 8 kHz that ranged from mild to moderate loss ^a	Backward span Modality: visual	No significant association

Table 2.1. (cont.)

Hällgren et al. (2001)	Cross-sectional	<u>NH</u> Young: $n = 12$, age = 27.8 (4.4) Older: $n = 12$, age = 69.5 (3.6) <u>HL</u> Young: $n = 12$, age = 27.1 (4.8) Older: $n = 12$, age = 69.8 (1.3)	Pure-tone thresholds obtained at 0.125, 0.25, 0.5, 1, 2, 3, 4, 6, & 8 kHz; NH and mild to moderate HL	Reading span Modality: visual	No significant association
Lunner (2003)	Cross-sectional	$n = 72$, age = 67.0	Mild to moderately severe loss; mean binaural PTA computed using thresholds at 100, 200, 500, 1000, & 2000 Hz; aided participants	Reading span Modality: visual	Significant negative association
Foo et al. (2007)	Cross-sectional	$n = 32$, age = 70.3 (7.7)	Mild to moderate loss; mean binaural PTA computed using 0.25, 0.5, 1, 2, 4, & 6 kHz; aided participants	Reading span, Letter monitoring Modality: visual	Significant negative association: PTA & accuracy on reading span task
Zekveld et al. (2007)	Cross-sectional	$n = 30$, age = 53.0 (14.0)	Mild loss; mean better ear PTA computed using pure-tone thresholds at 0.5, 1, & 2 kHz; unaided & aided participants	CANTAB spatial working memory Modality: visual	Significant negative association: PTA & CANTAB strategy score
Janse et al. (2014)	Cross-sectional	$n = 63$, age = 73.3 (5.3)	NH and mild loss; mean PTA computed using pure-tone thresholds at 1, 2, & 4 kHz; unaided participants	Backward digit span Modality: auditory	Significant negative association
Souza et al. (2015)	Cross-sectional	$n = 29$, age = 74.0	Mild to moderately severe loss based on thresholds at 0.5, 1, 2, & 3 kHz; & 3000 Hz; mean PTA not specified; aided participants	Reading span Modality: visual	No significant association

Table 2.1. (cont.)

Bruce et al. (2017)	Cross-sectional	<u>NH</u> : Young: $n = 29$, age = 21.8 (3.0) Older: $n = 26$, age = 65.2 (3.3) <u>HL</u> : Older: $n = 32$, age = 70.8 (5.8)	NH to mild loss; mean bilateral PTA computed using thresholds at 0.5, 1, 2, & 3 kHz; unaided participants	n -back Modality: auditory	No significant association
Guerreiro & Van Gerven (2017)	Cross-sectional	<u>NH</u> Young: $n = 54$, age = 22.0 (2.2) Older: $n = 22$, age = 66.1 (5.2) <u>HL</u> Older: $n = 22$, age = 66.7 (4.8)	NH to mild loss; mean better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided participants	n -back Modality: auditory & visual	Significant negative association
Nagaraj (2017)	Cross-sectional	$n = 24$, age = 66.9 (4.6)	Bilateral symmetric sensorineural HL; mean PTA not specified; unaided participants ^c	Reading, Listening span, Modality: visual, auditory	No significant association
Völter et al. (2017)	Cross-sectional	age = 65.8 (8.9) <u>NH</u> : $n = 80$ <u>HL</u> : severe to profound: $n = 40$	NH & severe-to-profound loss; better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; aided participants	n -back and operation span Modality: visual	Significant positive association: PTA & recall accuracy on operation span task ^d
Cervera et al. (2018)	Cross-sectional	<u>NH</u> : Young: $n = 28$, age = 21.7 (1.7) <u>HL</u> : Older: $n = 27$, age = 60.0 (5.0)	NH to moderate loss; mean better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided participants	Digit ordering Modality: auditory	Significant negative association
Jayakody et al. (2018)	Cross-sectional	<u>NH</u> : $n = 47$, age = 58.0 (9.2) <u>HL</u> : mild to moderate: $n = 51$, age = 67.5 (10.3), moderately severe to profound: $n = 21$, age = 67.4 (12.9)	NH to profound loss; better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided participants	CANTAB spatial working memory Modality: visual	Significant positive association: PTA & error percentage, CANTAB strategy score

Table 2.1. (cont.)

Na et al. (2018)	Cross-sectional	<u>NH</u> : $n = 26$, age = 74.0 (5.4) <u>HL</u> : mild: $n = 24$, age = 75.0 (5.6), moderate: $n = 28$, age = 74.6 (5.1), moderate-to-severe: $n = 22$, age = 75.2 (5.6)	NH to moderately severe HL; PTA computed using thresholds 0.5, 1, 2, & 4 kHz; unaided & aided participants	Backward digit span Modality: auditory	No significant associations
Nixon et al. (2019)	Cross-sectional	$n = 85$ age = 70.23 (5.17)	NH to profound HL; PTA computed using thresholds 0.5, 1, 2, & 4 kHz; unaided participants	1-back task Modality: visual	No significant association

Age: Mean (S.D.) years; PTA, pure-tone average; DSST, Digit Symbol Substitution Test; TMT-B, Trail Making Test-B; CST-C, Concept Shifting Task; LDST, Letter-Digit Substitution Test. ^aPure-tone average and details on amplification use not mentioned. ^bNegative beta co-efficients were obtained indicating poorer cognitive control. ^cDegree of hearing loss not mentioned. ^dInverse efficiency scores were derived on operation span with higher score indicating worse performance.

Table 2.2.

Summary of Studies on the Association between Speech-in-Noise Recognition and Cognitive Control in Individuals with ARHL

Study	Study type	Participant demographics	Audiological profile	Speech-in-Noise (SiN) task	Cognitive control task	Findings
<i>Cognitive flexibility</i>						
Woods et al. (2013)	Cross-sectional	<u>Normal hearing</u> Young: $n = 10$, age = 36.0 (14.0) <u>Hearing loss</u> Older: $n = 16$, age = 60.0 (12.0)	Hearing loss defined as pure-tone thresholds at 0.25, 5, 1, 2, 4, & 8 kHz exceeding 25 dB HL; mean PTA not specified; unaided & aided participants	NSRM sentences; single talker, single talker & speech-shaped noise, single talker, speech-shaped noise & four talker non-target NSRM sentences Measure: proportion correct	TMT-B Modality: visual	Significant negative association
Ellis & Munro (2015)	Cross-sectional	$n = 12$, age = 75.5	Moderate to severe high-frequency loss; mean PTA not specified; aided participants	IEEE sentences; 20-talker babble noise Measure: recall accuracy	TMT-B Modality: visual	Significant negative association
Ellis et al. (2016)	Cross-sectional	$n = 113$, age = 63.0	Mild ARHL; mean PTA not specified; aided participants	Hearing Bridge Speech-in-Noise test; speech-shaped noise Measure: SNR for 50% correct recognition	TMT-B Modality: visual	Significant positive association
<i>Inhibitory control</i>						
Janse (2012)	Cross-sectional	$n = 39$, age = 72.0 (4.9)	Mild loss; mean better ear PTA computed using pure-tone thresholds at 1, 2, & 4 kHz; unaided participants	Phoneme monitoring; competing talker Measure: hit rate	Stroop Modality: visual	Significant negative association

Table 2.2. (cont.)

Knight & Heinrich (2017)	Cross-sectional	$n = 50$, age = 69.5 (6.4)	Mild loss; mean PTA not specified; unaided participants	Isolated word recognition, RPSIN test; speech modulated noise Measure: recall accuracy	Stroop Modality: visual & auditory	Significant negative association: isolated word task & visual Stroop; significant positive association: isolated word task & auditory Stroop
van Knijff et al. (2018)	Cross-sectional	<u>Normal hearing</u> Young: $n = 25$, age = 47.0 (9.6) Older: $n = 17$, age = 70.0 (5.4) <u>Hearing loss</u> Older: $n = 9$, age = 74.0 (6.1)	Normal hearing to mild loss; mean better ear PTA computed using 0.5, 1, 2, & 4 kHz; unaided & aided participants	Spoken Dutch Corpus sentences; noise equaling long-term average speech spectrum Measure: recall accuracy	Adapted Simon task Modality: visual	Significant negative association
Knight & Heinrich (2019)	Cross-sectional	$n = 50$, age = 69.5 (6.4)	Mild loss; audiometric thresholds, mean PTA obtained at 0.25, 5, 1, 1.5, 2, 3, 4, 6 & 8 kHz; unaided participants	Isolated word recognition task, RSPIN test; speech modulated noise Measure: recall accuracy	Stroop Modality: visual & auditory	Significant negative association
<i>Working memory updating</i>						
Lunner (2003)	Cross-sectional	$n = 72$, age = 67.0	Mild to moderately severe loss; mean binaural PTA computed using thresholds at 0.1, 0.2, 0.5, 1, & 2 kHz; aided participants	Hagerman sentences; competing speech-shaped noise Measure: SNR for 40% correct speech recognition	Reading span task Modality: visual	Significant negative association
Foo et al. (2008)	Cross-sectional	$n = 32$, age = 70.3 (7.7)	Mild to moderate loss; mean binaural PTA computed 0.5, 1, 2, 4 & 6 kHz; aided participants	Hagerman sentences, HINT; unmodulated & modulated noise Measure: SNR for 80% correct recognition for Hagerman sentences, accuracy for HINT	Reading span task, Letter monitoring task Modality: visual	Significant negative association: Hagerman, HINT tasks & reading span &; Hagerman & visual letter monitoring

Table 2.2. (cont.)

Cervera et al. (2009)	Cross-sectional	<u>Normal hearing:</u> Young: $n = 28$, age = 21.7 (1.7) <u>Hearing loss:</u> Older: $n = 27$, age = 60.0 (5.0)	Normal hearing to moderate loss; mean better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided participants	Phoneme recognition; flat spectrum noise Measure: recall accuracy	Digit ordering Modality: visual	No significant association
Lunner & Sundewall-Thorén (2008)	Cross-sectional	$n = 23$, age = 65.6 (12.8)	Mild to moderate loss; mean PTA not specified; aided participants	Dantale II sentences; unmodulated & modulated noise Measure: SNR for 50% and 80% recognition	Visual letter monitoring task Modality: visual	Significant negative association
Rudner et al. (2012)	Cross-sectional	$n = 16$, age = 63.5 (12.1)	Mild to moderate loss; mean binaural PTA computed using 0.125, 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 6, & 8 kHz; aided participants	Dantale II sentences; modulated & steady state noise Measure: visual analog scale to rate listening effort, SNR for 50% word recognition	Visual letter monitoring task Modality: visual	Older adults with lower updating accuracy perceived SiN recognition as more effortful than adults with high accuracy
Arehart et al. (2013)	Cross-sectional	$n = 26$, age range = 62-92 years	Mild to moderate loss; mean PTA not specified; aided participants	IEEE sentences; quiet & 8-talker babble Measure: recall accuracy	Reading span task Modality: visual	Significant positive association
Ng et al. (2013)	Cross-sectional	$n = 26$, age = 59.0 (7.0)	Moderate to moderately severe loss; mean PTA computed using thresholds at 0.125, 0.25, 0.5, 1, 2, 3, 4, 6, & 8 kHz; aided participants	SWIR test containing HINT sentences; steady-state noise & four talker babble Measure: recall accuracy	Reading span task Modality: visual	Significant positive association
Souza & Sirow (2014)	Cross-sectional	$n = 27$, age = 82.1	Hearing loss defined as pure-tone thresholds ranging between 25-70 dB HL at 0.25, 5, 1, 2, 4, & 8 kHz; mean PTA not specified; aided participants	QuickSIN; four talker babble Measure: SNR for 50% correct recognition (QuickSIN score)	Reading span task Modality: visual	Significant negative association

Table 2.2. (cont.)

Heinrich et al. (2015)	Cross-sectional	$n = 44$, age = 65.3 (5.7)	Mild loss; mean better ear PTA computed using 5, 1, 2, & 4 kHz; unaided participants	DTT, adaptive Sentence List; speech-shaped noise, 8 Hz modulated noise Measure: SNR for 50% correct word recognition	Digit span backward, Letter monitoring test Modality: visual	Significant negative association: DTT & accuracy on backward digit span; no significant association between DTT and accuracy on letter monitoring task
Souza & Arehart (2015)	Cross-sectional	<u>Normal hearing</u> Young: $n = 30$, age = 24.0 (3.4) <u>Hearing loss</u> Older: $n = 94$, age = 69.0 (10.4)	Hearing loss defined as pure-tone thresholds at 0.25, 5, 1, 2, 4, & 8 kHz exceeding 25 dB HL; mean PTA not specified; unaided & aided participants	QuickSIN; four talker babble Measure: SNR for 50% correct recognition (QuickSIN score)	Variants of visual reading span task	Significant negative association
Souza et al. (2015)	Cross-sectional	$n = 29$, age = 74.0	Hearing loss defined as pure-tone thresholds ranging between 25-70 dB HL at 0.25, 5, 1, 2, 4, & 8 kHz; mean PTA not specified; aided participants	IEEE sentences; multi-talker babble Measure: recall accuracy	Reading span task Modality: visual	No significant association
Borch Petersen et al. (2016)	Cross-sectional	$n = 283$, age = 65.3 (12.2)	Mild to profound loss; mean better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; aided participants	Dantale II sentences; modulated & steady state noise Measure: SNR for 50% and 80% recognition	Reading span task Modality: visual	Significant negative association
Nagaraj (2017)	Cross-sectional	$n = 24$, age = 66.9 (4.6)	Bilateral symmetric sensorineural hearing loss; mean PTA not specified; unaided participants	RSPIN, QuickSIN; multi-talker babble Measure: recall accuracy	Reading span, listening span tasks Modality: visual & auditory	No significant association
Murphy et al. (2018)	Cross-sectional	$n = 77$, age = 60.3 (5.4)	Bilateral symmetric sensorineural hearing loss; mean PTA not specified; amplification use not specified	Brazilian SNT consisting of words; white noise Measure: recall accuracy	Digit span backward Modality: auditory	No significant association

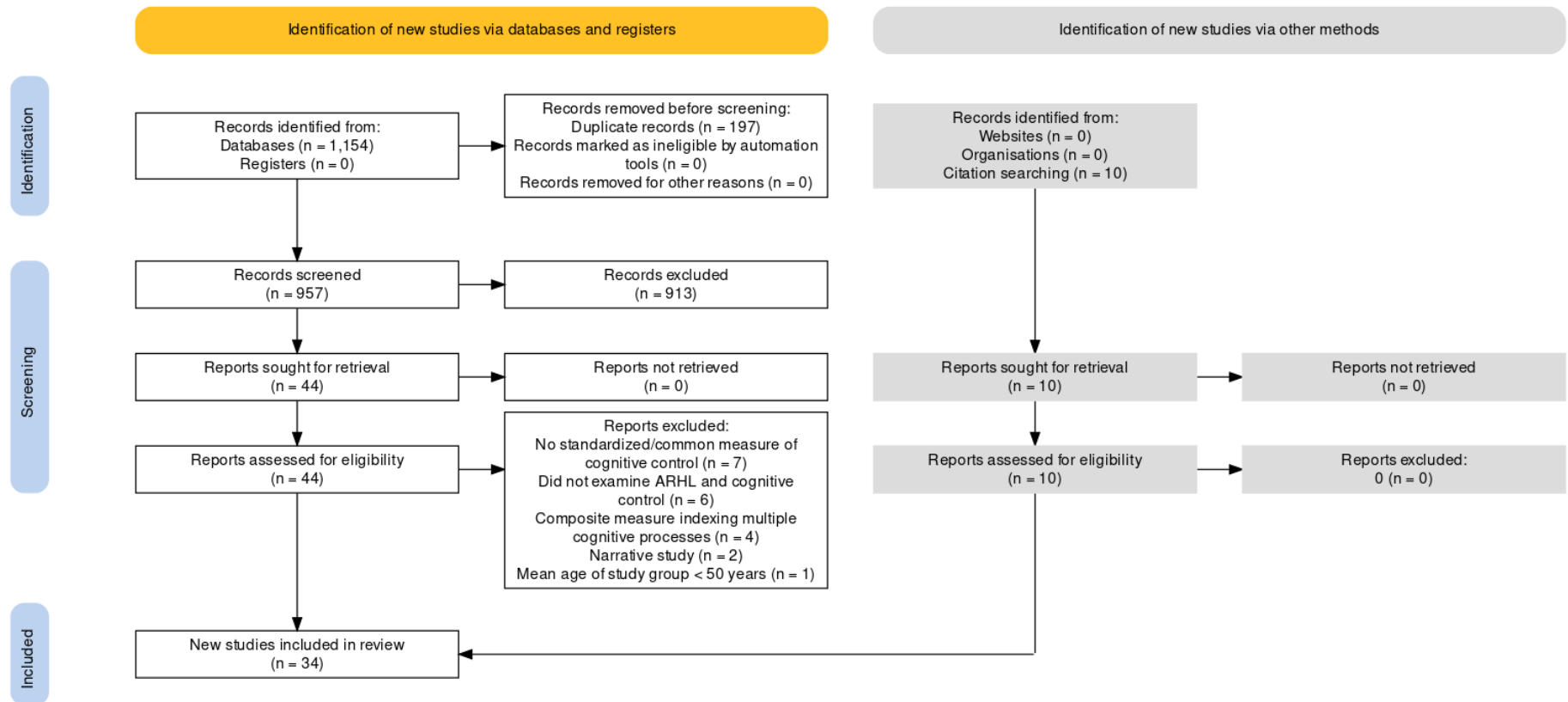
Table 2.2. (cont.)

Shehorn et al. (2018)	Cross-sectional	$n = 17$, age = 72.0 (7.6)	Mild to moderately severe loss; mean PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided & aided participants	RSPIN test; four talker babble Measure: recall accuracy	Reading span task Modality: visual	No significant association
Vermeire et al. (2019)	Cross-sectional	<u>Normal hearing</u> $n = 27$, age = 21.7 (1.3) <u>Hearing loss</u> $n = 33$, age = 71.0 (6.7)	Normal hearing & mild loss; mean better ear PTA computed using thresholds at 0.5, 1, 2, & 4 kHz; unaided & aided participants	LIST test; stationary speech-shaped noise Measure: SNR for 50% correct recognition	Reading span task Modality: visual	Significant negative association

Age: Mean (S.D.) years; PTA, pure-tone average; DTT, Digit triple test; IEEE, Institute of Electrical & Electronic Engineers; NSRM, Nonsense-Syllable Response Measure; RSPIN, Revised Speech Perception in Noise; HINT, Hearing in Noise Test; QuickSIN, Quick Speech-in-Noise; SWIR, Sentence final word identification & recall; LIST, Leuven Intelligibility Sentence Test; SNT: Speech-in-Noise Test.

Figure 2.1.

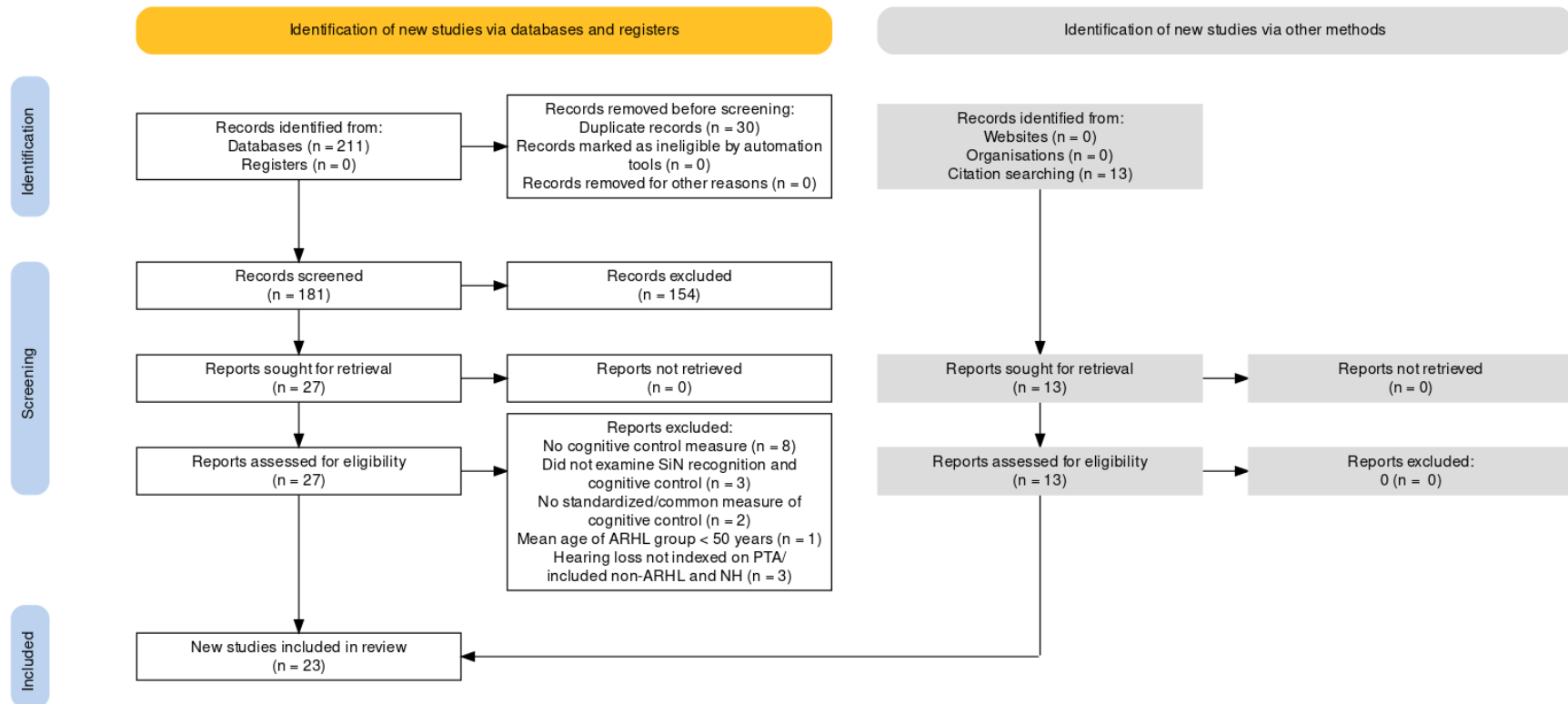
Study Selection Process for Review on Association between Peripheral Hearing Loss and Cognitive Control in Age-Related Hearing Loss



Note. Study selection process based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.
ARHL: Age-Related Hearing Loss.

Figure 2.2.

Study Selection Process for Review on Association between Speech-in-Noise Recognition and Cognitive Control in Age-Related Hearing Loss



Note. Study selection process based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. SiN: Speech-in-Noise; ARHL: Age-Related Hearing Loss; NH: Normal Hearing.

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Chapter 3. Cognitive Flexibility and Inhibitory Control in Age-Related Hearing Loss¹

Abstract

Growing evidence suggests alterations in cognitive control processes in individuals with varying degrees of age-related hearing loss (ARHL); however, alterations in those with unaided mild ARHL are understudied. The current study examined two cognitive control processes, cognitive flexibility and inhibitory control, in 21 older adults with unaided mild ARHL and 18 age- and education-matched normal hearing (NH) controls. All participants underwent comprehensive audiological and cognitive evaluations, including Trail Making Test-B, Verbal Fluency, Stroop, and two Go/NoGo tasks. Group differences in cognitive flexibility and inhibitory control, as well as associations between peripheral and central hearing ability and measures of cognitive flexibility and inhibitory control, were investigated. Findings revealed that the ARHL group took significantly longer to complete the Stroop task and had higher error rates on NoGo trials on both Go/NoGo tasks relative to the NH controls. Additionally, poorer peripheral and central hearing were associated with poorer cognitive flexibility and inhibitory control performance. Our findings suggest slower and more inefficient inhibitory control in the mild ARHL group relative to the NH group and add to decades of research on the association between hearing and cognition.

Keywords: age-related hearing loss; speech-in-noise recognition; hearing; cognitive flexibility; inhibitory control

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3.1. Introduction

Age-related hearing loss (ARHL) is the gradual loss of hearing with aging and is one of the most common conditions affecting older adults (Cruickshanks et al., 2003; Quaranta et al., 2015). In the United States, approximately one in three people between the ages of 65–74 years and one in two adults above 75 years are affected by ARHL (National Institute on Deafness and Other Communication Disorders, 2016). ARHL is typically characterized by deficits in peripheral and central hearing ability (Chmiel & Jerger, 1996; Humes et al., 2012). Peripheral hearing loss leads to deficits in the detection of sounds (e.g., rustling of leaves, doorbells, safety warnings such as smoke alarms; Arlinger, 2003; Huang & Tang, 2010) and is often associated with central hearing deficits, such as difficulties in discrimination of frequency and timing properties of sound, integration of sounds across both ears, and understanding speech, particularly in noisy environments, such as restaurants and crowded meeting rooms (Atcherson et al., 2015; Divenyi et al., 2005; Frisina & Walton, 2006; Humes & Young, 2016; Jerger et al., 1989). In fact, difficulty with recognition of speech-in-noise (SiN) is one of the hallmark symptoms of ARHL (Jerger et al., 1989; Tremblay & Ross, 2007). Numerous studies suggest that even individuals with milder degrees of hearing loss face significant speech recognition difficulties in noisy environments (Hällgren et al., 2001; Humes, 2002; Li-Korotky, 2012; Liljas et al., 2018). These deficits persist even when state-of-the-art amplification devices with noise reduction systems are used (Bentler, 2005; Kochkin, 2007), indicating that non-auditory factors may also be contributing to these deficits.

There is growing consensus that alterations in various cognitive faculties, such as episodic and semantic memory, speed of processing, and cognitive control (Arlinger, 2003; Boxtel et al., 2003; Bucks et al., 2016; Burgess et al., 2016; Hällgren et al., 2001; Lin, 2011; Lin

et al., 2011; Rönnberg et al., 2013) may contribute to the challenges experienced by older adults with ARHL (Humes, 2013; Humes et al., 2013; Janse, 2012; van Rooij & Plomp, 1990).

Cognitive control, also referred to as executive control, refers to a broad class of mental operations that allow information prioritization to accomplish current goals (Diamond, 2013; Mackie et al., 2013). Cognitive control includes processes such as *cognitive flexibility*, which is the ability to flexibly shift between tasks or mental sets of information; *inhibitory control*, which is the ability to suppress irrelevant information to allow processing of relevant information; and *working memory updating*, which is the ability to update and maintain incoming information over a short duration of time (Kane et al., 1994; Miyake et al., 2000). These processes are not specific to a particular modality, such as visual or auditory. In the context of ARHL, studies have predominantly investigated alterations in cognitive control processes by examining their associations with measures of peripheral hearing, primarily pure-tone average (PTA; Cervera et al., 2009; Foo et al., 2008; Granick et al., 1976; Guerreiro & Van Gerven, 2017; Harrison Bush et al., 2015; Janse, 2012; Lin, 2011; Lin et al., 2011; Ren et al., 2019; Souza et al., 2015), with some recently examining associations with central hearing measures, particularly SiN recognition (Ellis et al., 2016; Ellis & Munro, 2015; Foo et al., 2008; Knight & Heinrich, 2017, 2019; Lunner, 2003; Lunner & Sundewall-Thorén, 2008).

Of the cognitive control processes, alterations in working memory updating have been most extensively studied in individuals with ARHL. These studies have typically found alterations in accuracy measures of complex working memory updating tasks, such as Digit Ordering, Visual Letter Monitoring, *n*-back, and Reading Span (Cervera et al., 2009; Foo et al., 2008; Lunner & Sundewall-Thorén, 2008; Moore et al., 2014; Nagaraj, 2017). These deficits have been found in both auditory (Cervera et al., 2009; Guerreiro & Van Gerven, 2017) and visual (Lunner, 2003;

Lunner & Sundewall-Thorén, 2008; Nagaraj, 2017; Ng et al., 2013) modalities in individuals with varying degrees of hearing loss, including mild (Cervera et al., 2009; Foo et al., 2008; Guerreiro & Van Gerven, 2017; Jayakody et al., 2018; Lunner, 2003; Na et al., 2017; Souza et al., 2015; Zekveld et al., 2007), moderate (Cervera et al., 2009; Foo et al., 2008; Jayakody et al., 2018; Lunner, 2003; Souza et al., 2015), moderately severe (Jayakody et al., 2018; Lunner, 2003; Souza et al., 2015), and profound hearing loss (Jayakody et al., 2018), with greater severity of peripheral hearing loss associated with worse performance on updating measures. It is important to note that studies have found deficits in complex auditory working memory updating tasks despite presenting stimuli at suprathreshold levels (Cervera et al., 2009; Guerreiro & Van Gerven, 2017), indicating that alterations in working memory updating were not solely due to peripheral hearing deficits. A smaller subset of studies has found associations between working memory updating in ARHL and measures of complex SiN recognition, a metric of central hearing ability in ARHL (Arehart et al., 2013; Lunner, 2003; Lunner & Sundewall-Thorén, 2008; Ng et al., 2013; Rudner et al., 2012; Souza et al., 2015), supporting a link between alterations in working memory updating and central hearing ability.

Relative to working memory updating, fewer studies have examined cognitive flexibility in ARHL, with most using visual tasks. These studies have typically reported poorer accuracy on visual substitution measures such as the Digit Symbol and Letter Digit Substitution tests (Croll et al., 2020; Deal et al., 2015; Lin, 2011; Lin et al., 2013; Somnath et al., 2020), as well as longer completion time on the Trail Making Test-B (TMT-B; Harrison Bush et al., 2015; Huber et al., 2020; Lin et al., 2011; Ren et al., 2019) in older adults with ARHL compared to normal hearing (NH) controls. Studies have also found significant associations between peripheral hearing loss and performance on measures of cognitive flexibility. In particular, greater severity of peripheral

hearing loss has been associated with decreased accuracy on substitution tests and longer completion time on TMT-B. Similar findings have been observed in longitudinal studies involving older adults with ARHL ranging from mild (Lin et al., 2011; Valentijn et al., 2005) to severe degrees of hearing loss (Lin et al., 2011). Specifically, older adults with greater hearing loss severity have been found to have poorer accuracy on substitution tests over time despite hearing aid use. A handful of studies have also found a relationship between central hearing and cognitive flexibility in older adults with ARHL. Worse SiN recognition has been linked to decreased accuracy on substitution test (Croll et al., 2020) and longer completion time on TMT-B (Ellis et al., 2016; Ellis & Munro, 2015), especially when switching between multiple speech talkers was required (Woods et al., 2013), suggesting that slowing in cognitive flexibility is also related to central hearing ability in this population.

Also, fewer studies on ARHL have examined inhibitory control and the findings are rather inconclusive (Croll et al., 2020; Guerreiro & Van Gerven, 2017; Harrison Bush et al., 2015; Huber et al., 2020; Janse, 2012; Knight & Heinrich, 2017, 2019; Lin et al., 2011; Ren et al., 2019; van Knijff et al., 2018). While some have reported impairments in performance on visual Stroop measures, such as completion time (Ren et al., 2019), accuracy (Lin et al., 2011), and Stroop effect scores (which account for confounds of reading speed; Guerreiro & Van Gerven, 2017) in those with mild (Guerreiro & Van Gerven, 2017; Lin et al., 2011; Ren et al., 2019) to severe (Lin et al., 2011) peripheral ARHL as compared to NH controls, others have not found any group differences on measures of Stroop (Harrison Bush et al., 2015; Huber et al., 2020). Similarly, associations between peripheral hearing and inhibitory control are inconsistent. Some studies have found that greater hearing severity was related to longer completion times (Ren et al., 2019), lower accuracy (Lin et al., 2011), and worse Stroop effect scores (Croll et al., 2020;

Janse, 2012), whereas others have not reported such significant findings using the visual Stroop (Guerreiro & Van Gerven, 2017; Harrison Bush et al., 2015; Valentijn et al., 2005) and adapted Simon task (van Knijff et al., 2018). Evidence for associations between central hearing function measured using SiN recognition and inhibitory control in ARHL is inconclusive. While some have found significant associations between SiN recognition and the Stroop effect (Croll et al., 2020; Janse, 2012; Knight & Heinrich, 2017) and Simon effect scores (van Knijff et al., 2018), others have found no association between SiN recognition and performance on the Stroop task (Knight & Heinrich, 2017, 2019) in older adults with ARHL.

Given the discrepancy in findings related to cognitive flexibility and inhibitory control in individuals with ARHL, the goal of the current study was to concurrently examine these two processes in individuals with unaided mild ARHL compared to age- and education-matched NH controls. Additionally, we examined associations between measures of peripheral and central hearing and performance on tests of cognitive flexibility and inhibitory control. We hypothesized that (1) individuals with unaided mild ARHL would perform worse on measures of both cognitive flexibility and inhibitory control as compared to NH controls, (2) poorer peripheral hearing would be associated with poorer performance on measures of cognitive flexibility and inhibitory control, and poorer central hearing would be associated with worse performance on measures of cognitive flexibility and inhibitory control. Visual tasks of cognitive flexibility and inhibitory control were used to allow for comparison of our findings to existing literature.

3.2. Materials and Methods

3.2.1. Participants

Participants included 21 older adults with unaided mild ARHL (12 female; mean age: 71.29 ± 7.90 years; mean education: 17.76 ± 3.43 years) and 18 age- and education-matched NH

controls (12 female; mean age: 67.11 ± 5.46 years; mean education: 17.83 ± 1.65 years).

Demographic information for both groups is reported in **Table 3.1**. All participants were right-handed, native English speakers, and had normal or corrected vision with no history of learning disabilities, communication disorders, neurological disorders, psychiatric disorders, or traumatic brain injury. Individuals with a history of substance abuse, use of psychoactive medications, known etiologies of hearing loss, such as noise-induced, injury-related, or ototoxicity, and those with unilateral and/or bilateral continuous tinnitus, hearing aid use, and major vision problems (untreated cataracts, macular degeneration, glaucoma, retinopathy) were excluded. Additionally, participants completed the Montreal Cognitive Assessment (Nasreddine et al., 2005), a global cognitive screening measure, which was used to rule out individuals with possible cognitive impairment (cut-off score for exclusion: <26 ; ARHL mean score: 27.05 ± 2.18 ; NH mean score: 27.78 ± 1.86) and the Geriatric Depression Scale (Almeida & Almeida, 1999) to rule out those with depressive symptoms (cut-off score for exclusion: >5 ; ARHL mean score: 0.57 ± 0.97 ; NH mean score: 0.27 ± 0.57). All participants signed a written informed consent in accordance with protocol 17067 approved by the Institutional Review Board of the University of Illinois Urbana-Champaign before completing the study.

3.2.2. Audiological Evaluation

All participants underwent a comprehensive audiological assessment conducted by two audiologists who are also trained researchers. Assessments included otoscopic evaluation to rule out the presence of outer ear diseases, tympanometry to ensure normal middle ear function, reflexometry to rule out reflex pathway abnormalities, and pure-tone and speech audiometry. Pure tone audiometry was conducted in a sound-treated booth. Air conduction thresholds in each ear were obtained from 0.25 to 8 kHz with insert earphones as transducers using Equinox 2.0

audiometer calibrated (Interacoustics, Eden Prairie, MN, USA) to the American National Standards Institute S3.6 2010 standards (ANSI, 2010). Bone conduction thresholds were obtained from 0.25 to 4 kHz with a bone conduction transducer. All thresholds were determined using the modified Hughson-Westlake method (Carhart & Jerger, 1959) and were measured in decibels hearing level (dB HL). A speech-frequency PTA was calculated for air conduction thresholds at 0.5, 1, 2, and 4 kHz in each ear. Based on extant literature, NH was defined as ≤ 25 dB HL PTA in the better ear and ARHL was defined as > 25 dB HL PTA in the better ear (Lin et al., 2011, 2013). PTA score in the better ear was used as a measure of peripheral hearing.

Speech audiometry was conducted using insert ear transducers (ER-3A, Etymotic Research, Elk Grove Village, IL, USA). Speech Reception Thresholds (SRTs) using spondee words and Word Recognition Score (WRS) using the Northwestern University list 6 (Tillman & Carhart, 1966) were obtained in each ear to determine the presentation level for Quick Speech-in-Noise test (QuickSIN; Killion et al., 2004), the test used to assess central hearing. The QuickSIN test was administered in right, left, and both (binaural) ears. The QuickSIN task required participants to repeat back sentences presented against multi-talker babble at signal-to-noise ratios that varied in 5 dB steps from +25 dB to 0 dB. For all participants, the QuickSIN was presented at 70 dB HL as recommended (Killion et al., 2004), except for one participant for whom it was presented at their most comfortable level of 75 dB HL. QuickSIN scores were recorded, with higher scores suggesting worse SiN recognition. Binaural QuickSIN score was used as a measure of central hearing. Binaural scores were chosen as they represent the functional performance of using both ears in daily complex listening tasks.

3.2.3. Cognitive Flexibility and Inhibitory Control Evaluation

All participants completed a battery of cognitive control tests. Cognitive flexibility was assessed using the Verbal Fluency test, including Category Fluency (Goodglass et al., 2001) and Letter Fluency (Benton & Hamsher, 1976), the TMT-B (Reitan, 1958), and the Delis-Kaplan Executive Function System Stroop task (D-KEFS; Delis et al., 2001). Inhibitory control was assessed using the D-KEFS Stroop task and two experimental Go/NoGo tasks (Maguire et al., 2009; Mudar et al., 2015, 2016; Nguyen et al., 2017). Visual measures of cognitive flexibility and inhibitory control were selected in order to compare our findings with current studies that have largely used visual measures of cognitive control, as well as to minimize any confounds related to unaided hearing loss.

Verbal Fluency: As part of Verbal Fluency, both Category and Letter Fluency tasks were administered. Category Fluency required participants to recall as many animals as possible in one minute and Letter Fluency involved recall of as many words as possible that began with the letters F, A, and S, with one minute for each letter. The total number of animals recalled and the sum of recalled words beginning with F, A, and S were computed, with higher scores indicating better cognitive flexibility performance.

TMT-B: TMT-B required participants to draw a line to connect letters and numbers in alternating and ascending order (e.g., 1-A-2-B). Completion times were recorded, with longer completion times indicating poorer cognitive flexibility performance.

D-KEFS Stroop: Stroop was administered and scores on two conditions, the color-word interference condition and the color-word interference/switching condition, were obtained. The interference condition required participants to say out loud the ink color in which the color name was written out (e.g., say *red* for color name blue written in red ink) as quickly and accurately as

possible. In the interference/switching condition, participants were required to switch between saying the ink color (e.g., say *red* for color name blue written in red ink) and reading the color name itself (e.g., say *blue* for color name blue written in red ink). Switching was cued by boxes drawn around certain words (boxed words require reading the color name) and not around others (unboxed words require saying the ink color). Completion times were recorded for both interference and interference/switching conditions. Mixing cost was calculated by subtracting the completion time on the interference condition from the interference/switching condition. Completion time on the color-word interference condition was used as a measure of inhibitory control with longer completion times indicating poorer inhibitory control performance. Mixing cost was used as a measure of cognitive flexibility, with higher Stroop mixing cost reflecting poorer cognitive flexibility.

Go/NoGo Tasks: Participants performed two Go/NoGo tasks, one requiring basic categorization, “Single-Car”, and one requiring superordinate categorization, “Object-Animal”, with the latter being the more complex task requiring careful evaluation of both perceptual and semantic features of stimuli. Details on the development of these tasks can be found in Maguire et al. (2009) and both tasks have been successfully used in several studies involving older adults (Mudar et al., 2015, 2016; Nguyen et al., 2017). In the Single-Car task, participants viewed line-drawn exemplars of a single “car” and a single “dog” 160 and 40 times, respectively, on a computer screen. Basic levels of “car” and “dog” were used for correct discrimination using basic classification (car vs. dog) instead of superordinate classification (vehicle vs. animal). Participants were required to make Go/NoGo decisions, where a button push response was required for “car” (Go) but not for “dog” (NoGo). These decisions were to be as quick and accurate as possible. In the Object-Animal task, participants viewed multiple line-drawn

exemplars of “objects” and “animals” 160 and 40 times, respectively. Exemplars of objects consisted of 40 food items, 40 cars, 20 clothing items, 20 kitchen items, 20 human body parts, and 20 tools, and exemplars of animals consisted of items with varying visual typicality, such as cat, snake, elephant, and lobster. Participants were asked to make quick and accurate Go/NoGo decisions, where a button push was required for “objects” (Go) but not for “animals” (NoGo). Both the Single-Car and Object-Animal tasks consisted of 80% (160) Go trials and 20% (40) NoGo trials. This distribution was used to accentuate the tendency for pre-potent responses. Order and practice effects were minimized by pseudo-randomization of the sequence of stimuli in each task, and task order was counterbalanced for each participant. For each task, a Compumedics NeuroScan Stim System Switch response pad (button-box) was used to register Go responses and record reaction times (RTs), and error rate was calculated for Go and NoGo responses.

3.2.4. Statistical Analysis

The data were analyzed using IBM SPSS Statistics (Version 26, IBM Corp., Armonk, NY, USA). General linear models (GLMs) were used to examine between-group (ARHL/NH) differences in demographic and audiological factors. GLMs were also used to examine group differences in performance on measures of cognitive control tasks with group (ARHL/NH defined on basis of PTA) as a between-subject variable and measures of cognitive flexibility (total number of words recalled on Verbal Fluency tasks; completion time on the TMT-B; Stroop mixing cost) and inhibitory control (completion time on the color-word interference condition of the Stroop task; RTs/error rate on trials of Go/NoGo tasks) as within-subject variables. Bonferroni corrections were used to correct for multiple comparisons with alpha set at 0.05. The

p-values reported in the Results section are significant effects derived from *F*- statistics of contrasts of experimental factor means.

We conducted primary and secondary analyses to examine correlations between hearing and cognitive control measures. For primary analyses, Pearson's method was used to examine zero-order correlations between peripheral hearing ability (assessed using PTA) and performance on cognitive flexibility and inhibitory control measures. With regard to Go/NoGo tasks, correlational analyses were restricted to NoGo trials since they reflect inhibitory control as opposed to Go trials which reflect response execution (Littman & Takács, 2017). Given that central hearing is closely associated with peripheral hearing (Akeroyd, 2008; Humes et al., 2013), we conducted partial correlations to examine the relationship between central hearing ability and performance on cognitive flexibility and inhibitory control measures while controlling for peripheral hearing ability.

As part of our secondary analyses, we examined associations between low- and high-frequency peripheral hearing loss and performance on measures of cognitive flexibility and inhibitory control. These secondary analyses were motivated by an emerging body of research suggesting that these sub-types of hearing loss are distinctly related to cognition (Brännström et al., 2018; Eckert et al., 2012, 2019). We derived low- and high-frequency hearing measures from pure tone thresholds using the method outlined in Eckert et al. (Eckert et al., 2012, 2019; see supplementary materials for details). This approach involves calculation of low- and high-frequency hearing based on a factor analysis of pure tone thresholds from 852 older adults (mean age = 69.92 ± 7.24 years) who participated in a study on ARHL (Dubno et al., 2008; Lee et al., 2005). However, unlike the approach used in Eckert et al. (Eckert et al., 2012, 2019), wherein low- and high-frequency hearing across the right and left ear were averaged, we calculated low-

and high-frequency hearing for the ear with better PTA. We then examined zero-order correlations between low-frequency hearing and performance on cognitive flexibility and inhibitory control; and high-frequency hearing and performance on cognitive flexibility and inhibitory control measures. All correlational analyses were conducted after dropping outliers (± 2 standard deviations from the mean score of the variables being assessed). Accordingly, we dropped two outliers each for PTA, Binaural QuickSIN, Category Fluency, Stroop mixing cost, error rate on NoGo trials of the Object-Animal Task as well as low- and high-frequency hearing measures; and one outlier each for TMT-B, Letter Fluency, interference condition of D-KEFS Stroop task, and error rate on NoGo trials of the Single-Car task.

3.3. Results

3.3.1. Group Differences

Audiological Measures: Main effects of group were observed for the following audiological measures: PTA, $F_{(1,37)} = 62.49$, $p < 0.001$; right ear SRT, $F_{(1,37)} = 19.49$, $p < 0.001$; left ear SRT, $F_{(1,37)} = 36.66$, $p < 0.001$; right ear QuickSIN score, $F_{(1,37)} = 14.40$, $p = 0.001$; left ear QuickSIN score, $F_{(1,37)} = 8.96$, $p = 0.005$, and binaural QuickSIN score, $F_{(1,37)} = 8.63$, $p = 0.006$. Significantly higher PTA, SRT, and QuickSIN scores were observed for the ARHL compared to the NH group. All other effects were not significant. Group means for all audiological measures are reported in **Table 3.2**. Audiograms for NH and ARHL groups are shown in **Figure. 3.1**.

Cognitive Flexibility and Inhibitory control Measures: A main effect of group was observed for completion time on the Stroop color-word interference condition, $F_{(1,37)} = 6.14$, $p = 0.018$, with significantly longer completion times in the ARHL group compared to the NH group. A main effect of group was observed for error rate on NoGo trials for both Single-Car,

$F_{(1,37)} = 5.10, p = 0.030$, and Object-Animal tasks, $F_{(1,37)} = 6.45, p = 0.016$, with higher error rate in the ARHL group compared to the NH group. All other effects were not significant. Group means for all cognitive control measures are reported in **Table 3.3**.

3.3.2. Correlations

Several significant associations between hearing measures and measures of cognitive flexibility and inhibitory control were observed. With regard to our primary analyses related to cognitive flexibility, we found a significant positive correlation between PTA and completion time on the TMT-B, $r(32) = 0.36, p = 0.034$. When partial correlations between binaural QuickSIN score and measures of cognitive flexibility were examined controlling for PTA, a significant positive correlation between binaural QuickSIN score and TMT-B, $r(31) = 0.57, p < 0.001$, and a significant negative correlation between binaural QuickSIN score and Letter Fluency score, $r(31) = -0.36, p = 0.038$, were observed. Our secondary analyses found no significant correlations between measures of low- and high-frequency hearing and cognitive flexibility.

On our primary correlational analyses involving inhibitory control, we found significant positive correlations between PTA and completion time on the Stroop color-word interference condition, $r(31) = 0.42, p = 0.013$, and between error rate on NoGo trials of the Object-Animal task, $r(31) = 0.39, p = 0.022$. When we examined partial correlations between binaural QuickSIN score and measures of inhibitory control while controlling for PTA, we observed a significant positive correlation between binaural QuickSIN score and error rate on NoGo trials of the Object-Animal task, $r(30) = 0.50, p = 0.003$. Additionally, as part of our secondary analyses, we found a significant positive correlation between better ear high-frequency hearing and completion time on the Stroop color-word interference condition, $r(31) = 0.46, p = 0.006$. No

other correlations were significant. Scatter plots for all significant associations with primary analyses are shown in **Figure 3.2** (see Supplementary Figure 3.1 for scatter plots for non-significant associations). All correlations with primary analyses are reported in **Table 3.4** (see Supplementary Table 3.2 for associations with secondary analyses).

3.4. Discussion

This study examined differences in performance on measures of cognitive flexibility and inhibitory control between older adults with unaided mild ARHL and NH controls, and associations between measures of peripheral hearing, central hearing, and measures of cognitive flexibility and inhibitory control. As expected, we found significant differences between ARHL and NH groups on both peripheral (PTA) and central (binaural QuickSIN scores) hearing measures. The ARHL group had higher PTA and binaural QuickSIN scores relative to NH group, reflecting poorer peripheral and central hearing in this population. Three major findings related to the goals of our study emerged: (1) the ARHL group performed worse on measures of inhibitory control (completion time on the Stroop color-word interference condition and error rate on NoGo trials of Go/NoGo tasks) relative to the NH group, with no significant group differences observed on measures of cognitive flexibility (total number of words recalled on Verbal Fluency tasks, completion time on TMT-B, and Stroop mixing cost), (2) significant associations were observed between measures of hearing and cognitive flexibility (completion time on TMT-B and number of words recalled on Letter Fluency), and (3) significant associations were observed between measures of hearing and inhibitory control (completion time on the Stroop color-word interference condition and error rate on NoGo trials of the Object-Animal Go/NoGo task). Additionally, on secondary analyses, we observed that high-frequency

hearing measure was associated with longer completion time on the Stroop color-word interference condition.

3.4.1. Inhibitory control

Findings related to group differences revealed that the ARHL group demonstrated not only slower, but also worse, inhibitory control. On the Stroop color-word interference condition, the ARHL group took longer to complete the task relative to the NH group, which is consistent with the findings of most prior studies (Guerreiro & Van Gerven, 2017; Huber et al., 2020; Ren et al., 2019), with two exceptions (Harrison Bush et al., 2015; Huber et al., 2020). Our finding suggests that the ARHL group required more time to successfully employ inhibitory control to perform the task with the same accuracy level as the NH group. Furthermore, we found that the ARHL group had higher error rates on NoGo trials on both the simpler Single-Car and the more complex Object-Animal Go/NoGo tasks relative to the control group. The ARHL group's ability to inhibit their pre-potent responses for the infrequently occurring NoGo trials (20% of the total trials) appears to be worse than that of the NH group leading to higher error rates (i.e., false alarms), indicating inhibitory control deficits.

Although Go/NoGo tasks have been used extensively in studies with normal cognitive aging and various clinical populations (Mudar et al., 2015, 2016; Nguyen et al., 2017; Vallesi, 2011), they have rarely been used in the context of ARHL with the exception of Kuchinsky et al. (2016). Kuchinsky and colleagues used RTs of Go trials as a measure of vigilance and found no relation between PTA and performance on Go trials. Similarly, we did not find a significant group difference on RTs and error rates on Go trials, which suggests that older adults with mild ARHL were able to successfully allocate their attentional resources similar to controls to respond to the frequently occurring Go trials (80% of the trials). However, Kuchinsky et al. (2016) did

not analyze performance on the NoGo trials, therefore our findings related to NoGo trials need to be corroborated in future studies. Additionally, they utilized letters as stimuli for their Go/NoGo task whereas the current study used more complex stimuli of line drawings of animals and objects. How task and/or stimulus complexity may affect inhibitory control performance in individuals with ARHL requires further examination in studies that compare performance on inhibitory control tasks involving both simple and complex stimuli. Overall, our findings suggest that cognitive alterations in inhibitory control appear to occur even with milder degrees of hearing loss. One could argue that these alterations in inhibitory control are typical in older adults, as has been extensively documented in the body of work on normal cognitive aging (Anderson & Craik, 2017; Hartmann et al., 2019; Hasher et al., 1991, 2007; Hu et al., 2018; Kane et al., 1994; Lustig et al., 2008; McDowd, 1997). However, given that we included age-matched NH controls, alterations observed in our ARHL group are above and beyond those typically related to normal aging.

Our primary correlational analyses revealed that inhibitory control is related to peripheral and central hearing abilities. Our findings showed a positive association between peripheral hearing measure (PTA) and completion time on the Stroop color-word interference condition, where older adults with higher PTA took longer to complete the color-word interference condition (i.e., they were slower). Our findings are consistent with others who have examined associations between peripheral hearing and inhibitory control measures (Croll et al., 2020; Janse, 2012; Lin et al., 2011; Ren et al., 2019). We also observed positive associations between PTA and error rates, as well as binaural QuickSIN score and error rates on the NoGo trials of the more complex Object-Animal Go/NoGo task. Older adults with higher PTA and binaural QuickSIN scores made more errors (higher false alarms) on the NoGo trials. Given that we did

not observe similar associations with the simpler Single-Car Go/NoGo task, this indicates that the link between hearing and inhibitory control is modulated by task complexity. The Object-Animal task requires a more involved examination of both perceptual and semantic features compared to the Single-Car task. Additionally, given that the significant association between binaural QuickSIN scores and error rates was observed even when PTA was partialled out, the association between central hearing and inhibitory control appears to go beyond peripheral auditory deficits. The QuickSIN task requires participants to repeat back sentences while ignoring multi-talker babble in the background, thus, requiring inhibitory control. As such, our findings of association between binaural QuickSIN scores and performance on the Object-Animal task add to the literature on the links between inhibitory control and SiN recognition found by others in younger and older adults with NH (Humes & Young, 2016; Sommers & Danielson, 1999; Stenbäck et al., 2015), and in those with ARHL (Janse, 2012; Knight & Heinrich, 2017, 2019).

As part of our secondary analyses, we found a significant positive association between high-frequency hearing measure and completion time on the Stroop color-word interference condition, suggesting that poor high-frequency hearing is associated with slower inhibitory control. Our finding converges with a study by Brännström et al. (2018) who also found that poorer high-frequency hearing was associated with poorer inhibitory control on a sustained attention response task. However, it is important to note that Brännström et al. (2018) analyzed extended high frequencies (10, 12.5, and 14 kHz) in individuals with NH, unlike our high-frequency hearing measure which included frequencies from 0.25 to 8 kHz. Future investigation in this emerging area is required to better understand how hearing is linked to inhibitory control in older adults with ARHL.

3.4.2. Cognitive Flexibility

With regard to cognitive flexibility, we found no significant group differences; however, we observed significant associations between peripheral hearing and cognitive flexibility as well as central hearing and cognitive flexibility. We found a significant positive association between peripheral hearing measure (PTA) and completion time on the TMT-B, which is consistent with previous studies using similar measures (Harrison Bush et al., 2015; Huber et al., 2020; Lin, 2011; Ren et al., 2019; Valentijn et al., 2005). This finding suggests that decreased hearing ability is related to slowing in cognitive flexibility. It has been suggested that responding during pure-tone audiometry might involve some amount of cognitive flexibility since it involves deciding whether a sound is present or absent on each trial across frequencies (Brännström et al., 2020).

We also found a significant positive association between a central hearing measure, binaural QuickSIN score, and completion time on the TMT-B, indicating that poorer recognition of sentences in background noise is associated with slowing in cognitive flexibility. Furthermore, we found a significant negative association between binaural QuickSIN score and number of recalled words on the Letter Fluency task, which suggests that poorer sentence recognition in background noise is also related to alterations in cognitive flexibility. Spoken word recognition models propose that during speech recognition, a corpus of mental representations of words are activated and listeners choose those mental representations that best match the bottom-up input i.e., spoken speech (see Sommers & Danielson, 1999). It is likely that cognitive flexibility is required to successfully shift between the different mental representations of words to aid correct matching of the incoming word, especially in noise. Our findings of association between QuickSIN scores and performance on cognitive flexibility tasks align with previous studies that

have observed associations between worse SiN recognition and longer TMT-B completion times (Ellis et al., 2016; Ellis & Munro, 2013, 2015; Woods et al., 2013) and a lower number of recalled words on the Letter Fluency task (Classon et al., 2014). One could argue that the association between binaural QuickSIN score and TMT-B is confounded by speed of processing. A posteriori analysis showed no change in the association between binaural QuickSIN score and TMT-B when speed of processing was controlled for (TMT-A was used as a control variable; TMT-A requires participants to connect only numbers in ascending order, as opposed to shifting between numbers and letters in TMT-B, and indexes processing speed; see Supplementary Table 3.3). Furthermore, given that the significant associations between binaural QuickSIN scores and completion time on TMT-B and Letter fluency scores were observed even when the effect of PTA was controlled, these findings suggest that the association between central hearing and cognitive flexibility is above and beyond what is linked to peripheral auditory deficits. However, the mechanism and underlying nature of the association between SiN recognition and cognitive flexibility is far from clear and requires further investigation.

Decades of research have suggested that sensory ability, including hearing, is linked to cognitive performance (Baltes & Lindenberger, 1997; CHABA, 1988; Cohen, 1987; Humes, 2020; Lindenberger & Baltes, 1994; Pichora-Fuller, 2003, 2015; van Rooij & Plomp, 1990, 1992; Whitson et al., 2018) and our study adds to this vast literature. Several theoretical frameworks have long proposed hypotheses to explain the connection between hearing and cognition, such as the information-degradation, sensory-deprivation (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994), and the common-cause hypotheses (Baltes & Lindenberger, 1997; CHABA, 1988; Lindenberger & Baltes, 1994), but our study was not designed to examine or explore any of these hypothesized connections. Our study was purely exploratory in nature

and was motivated by a desire to understand whether we might observe group differences in cognitive flexibility and inhibitory control between unaided mild ARHL and NH groups in a cross-sectional sample and to understand associations between hearing and cognitive control within this sample. Although we did observe significant findings both in analyses of group differences and correlations, our findings are not generalizable given our small sample size. Replication studies and future investigations with more participants are necessary to truly understand the nature of alterations in cognitive flexibility and inhibitory control in older adults with mild ARHL.

One of the goals of our study was to separately explore how peripheral hearing and central hearing measures varied in their relationship to cognitive flexibility and inhibitory control. As the first step in this direction, we examined peripheral hearing using PTA, a threshold measure, and central hearing ability using QuickSIN task, a suprathreshold measure. Future work should consider a more comprehensive evaluation of peripheral and central auditory functioning. For example, the QuickSIN task used in this study measured one of the primary central auditory functions, i.e., auditory performance with competing acoustic signals. Examining other central auditory functions, such as auditory discrimination and pattern recognition, and temporal and frequency resolution may shed more light on the link between hearing and cognitive control in ARHL and its potential link to cognitive health. This would be especially important in light of increasing evidence that suggests impairment in central auditory functions may be an early indicator of cognitive decline (Edwards et al., 2017; Gates et al., 2011; Kurylo et al., 1993; Sardone et al., 2020; Swords et al., 2018; Tuwaig et al., 2017).

Our sampling of measures for cognitive flexibility and inhibitory control was narrow. Concurrent examination of different cognitive control processes, such as cognitive flexibility,

inhibitory control, and working memory updating, with multiple measures for each and assessed using both visual and auditory modalities, will be necessary to comprehensively characterize cognitive control alterations in this population. Finally, participation in our study was restricted to those with unaided hearing loss. The impact of aided hearing on cognitive flexibility and inhibitory control and whether aided hearing helps mitigate these alterations needs further exploration. To fully understand the nature of cognitive flexibility and inhibitory control alterations in ARHL, a multi-disciplinary investigative approach, including a combination of behavioral, neuroimaging, and electrophysiological techniques in both cross-sectional and longitudinal studies, is critical.

3.5. Tables and Figures

Table 3.1.

Demographic Characteristics of Participants

	ARHL Group	NH Group
Total N	21	18
Age (years)	71.29 (7.90)	67.11 (5.46)
Education (years)	17.76 (3.43)	17.83 (1.65)
Sex	12F/9M	12F/6M

Cells represent mean (standard deviation). ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Table 3.2.

Group Means for Audiological Measures

	ARHL Group	NH Group	p-value
Better ear PTA (dB HL)	32.61 (6.69)	16.59 (5.82)	<.001*
Right SRT (dB HL)	31.19 (9.60)	19.72 (5.80)	<.001*
Left SRT (dB HL)	31.67 (6.58)	19.44 (5.91)	<.001*
Right WRS (%)	94.29 (10.62)	98.44 (2.79)	.116
Left WRS (%)	94.67 (8.61)	98.22 (4.79)	.128
Right QuickSIN	6.00 (3.15)	2.80 (1.79)	.001*
Left QuickSIN	5.69 (3.26)	3.02 (2.02)	.005*
Binaural QuickSIN	3.69 (2.86)	1.58 (1.08)	.006*

Cells represent means of raw test scores (standard deviation). ARHL = Age-Related Hearing Loss; NH = Normal Hearing; PTA (dB HL) = Pure-Tone Average (decibels hearing level); SRT (dB HL) = Speech Reception Threshold (decibels hearing level); WRS (dB HL) = Word Recognition Score (decibels hearing level); QuickSIN = Quick Speech-in-Noise (Killion et al., 2004). Values in bold represent significant effects.

* $p < .05$.

Table 3.3.*Group Means for Cognitive Control Measures*

	ARHL Group	NH Group	p-value
Category Fluency	20.38 (4.96)	22.72 (4.95)	.150
COWAT - Letter Fluency	43.29 (12.38)	48.28 (12.80)	.224
TMT-B (s)	77.11 (25.28)	65.27 (16.49)	.098
Stroop mixing cost	5.90 (17.50)	8.89 (17.54)	.599
Stroop color-word interference (s)	62.62 (13.41)	53.39 (8.99)	.018*
SC RT ^a (ms)	350.25 (51.58)	343.51 (35.85)	.647
SC Go error ^a (%)	0.04 (0.10)	0.96 (0.16)	.306
SC NoGo error ^a (%)	0.14 (0.10)	0.08 (0.05)	.030*
OA RT ^a (ms)	420.85 (40.65)	438.10 (36.74)	.180
OA Go error ^a (%)	0.05 (0.06)	0.04 (0.07)	.618
OA NoGo error ^a (%)	0.18 (0.21)	0.05 (0.05)	.016*

Cells represent means of raw test scores (standard deviation). ARHL = Age-Related Hearing Loss; NH = Normal Hearing. ^aARHL Group, n=20. TMT = Trail Making Test (Reitan, 1958); COWAT = Controlled Oral Word Association Test (Benton & Hamsher, 1976); SC = Single-Car Task; OA = Object-Animal Task; RT = reaction time. Values in bold represent significant effects

* $p < .05$

Table 3.4.*Correlations between Hearing and Cognitive Control Measures*

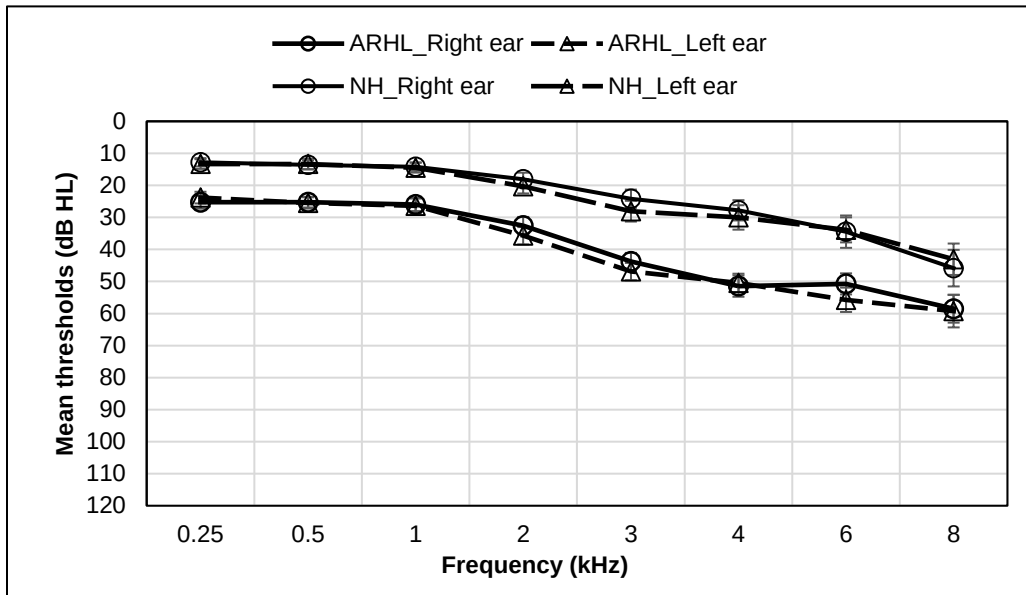
	PTA (dB HL)^a	Binaural QuickSIN Score^b
<i>Cognitive Flexibility</i>		
Category Fluency	-0.25	-0.26
COWAT - Letter Fluency	-0.21	-0.36*
TMT-B (s)	0.36*	0.57*
Stroop mixing cost	-0.10	0.05
<i>Inhibitory Control</i>		
Stroop color-word interference (s)	0.42*	0.20
SC NoGo error (%)	0.33	0.41
OA NoGo error (%)	0.39*	0.50*

^aCorrelations with PTA (dB HL) are zero-order correlation coefficients. ^bCorrelations with Binaural QuickSIN scores are partial correlation coefficients. PTA (dB HL) = Pure-Tone Average (decibels hearing level); QuickSIN = Quick Speech-in-Noise (Killian et al., 2004); TMT = Trail Making Test (Reitan, 1958); COWAT = Controlled Oral Word Association Test (Benton & Hamsher, 1976); SC = Single-Car Task; OA = Object-Animal Task. Values in bold represent significant effects.

* $p < 0.05$

Figure 3.1.

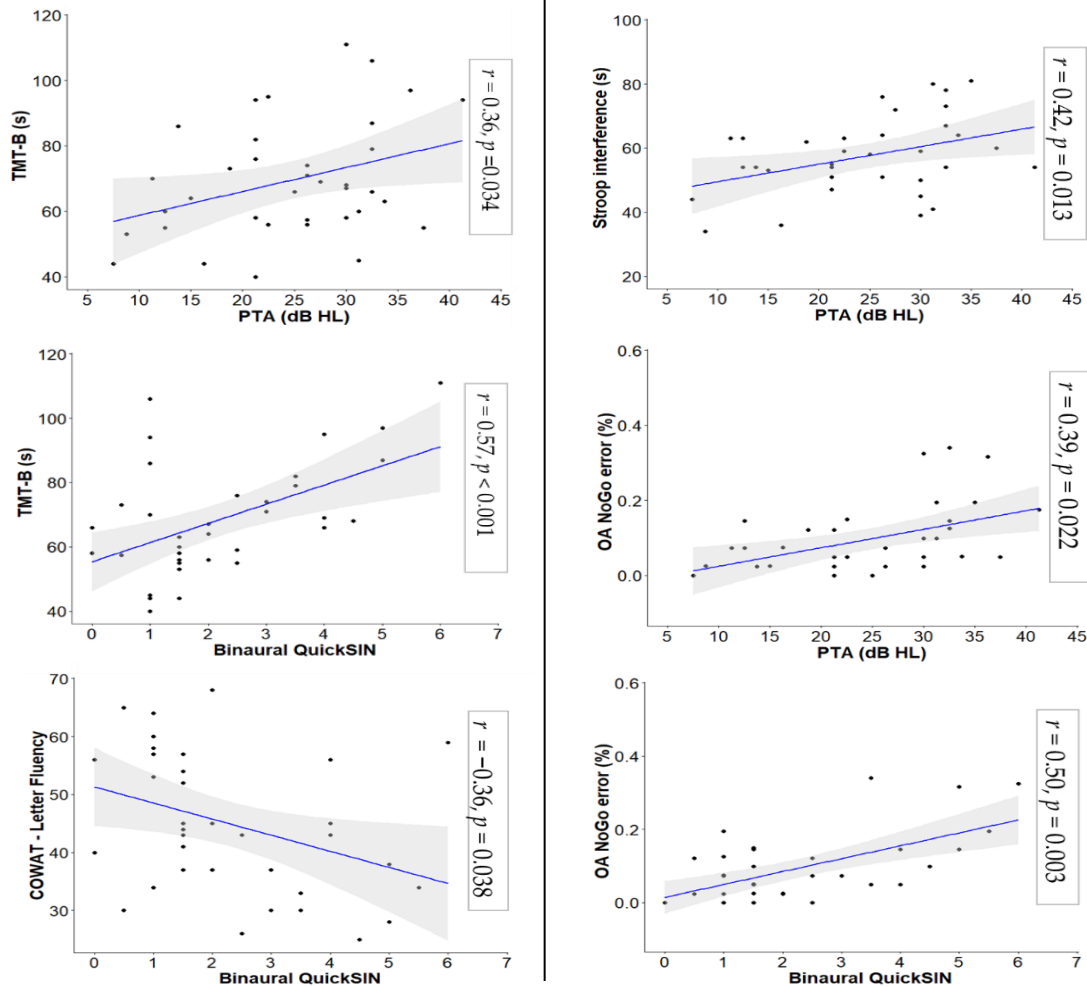
Audiogram for ARHL and NH groups



Average of air conduction hearing thresholds for both ears across frequencies in Age-Related Hearing Loss (ARHL) and Normal Hearing (NH) groups. Error bars represent standard errors.

Figure 3.2.

Significant Relationships between Hearing and Cognitive Control Variables



PTA (dB HL) = Pure-Tone Average (decibels hearing level); QuickSIN = Quick Speech-in-Noise (Killion et al., 2004); TMT-B = Trail Making Test B (Reitan, 1958); COWAT = Controlled Oral Word Association Test (Benton & Hamsher, 1976); OA = Object-Animal Task.

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3.7. Supplementary Materials

Calculation of Low-frequency and High-frequency Measures

We used the methodology detailed in Eckert et al., 2012, 2019 studies for calculating the low- and high-frequency hearing measures for our secondary analyses. The steps to derive these measures are listed as follows: (1) Each participants' pure-tone thresholds for each ear (from 0.25 to 8 kHz frequencies) were standardized to the mean and standard deviation of the corresponding pure-tone threshold from the 852 older adults (columns 2 and 3 in Supplementary Table 3.1, reproduced from Eckert et al., 2012). For example, a participant with a 30-dB HL threshold at 250 Hz would have a standardized score for that threshold equal to 1.047 ($x = [30 - 17.37] / 12.06$). (2) This standardized score was then multiplied by the corresponding low- and high-frequency component coefficient from the factor analysis (columns 4 and 5 in Supplementary Table 3.1, reproduced from Eckert et al., 2012). For example, the same participant from above would have a weighted low-frequency score equal to 0.424 ($x = 1.047 * 0.405$) and a weighted high-frequency score equal to -0.145 ($x = 1.047 * -0.139$) for the threshold at 250 Hz. (3) We then summed these weighted values across frequencies (0.25 to 8 kHz) for each component, and thus, created the low- and high-frequency hearing measures. (4) Based on the ear which had better PTA, we used better ear low-frequency and high-frequency measures. For example, if a participant had better PTA in the right ear, then we used the low- and high-frequency measures of the right ear.

Supplementary Table 3.1.

Values for Calculation of Low- and High-Frequency Measures

Descriptive statistics and factor analysis coefficients that can be used to estimate low and high frequency hearing threshold components				
Frequency (Hz)	Mean	SD	Component score co-efficient matrix	
			Low frequency component	High frequency component
250	17.37	12.06	0.405	-0.139
500	17.70	13.29	0.420	-0.137
1,000	20.05	15.48	0.316	-0.039
2,000	29.44	19.97	0.096	0.137
3,000	38.63	22.81	-0.065	0.253
4,000	47.14	23.98	-0.112	0.280
6,000	55.31	24.19	-0.101	0.273
8,000	58.57	23.69	-0.081	0.248

From Eckert et al., 2012. (Table 1, pg. 707). Reprinted with Permission from the Springer Nature Customer Service Center GmbH: Springer Nature. Eckert, M. A., Cute, S. L., Vaden, K. I., Kuchinsky, S. E., & Dubno, J. R. (2012). Auditory cortex signs of age-related hearing loss. *JARO - Journal of the Association for Research in Otolaryngology*, 13(5), 703–713. <https://doi.org/10.1007/s10162-012-0332-5>. Copyright Clearance Center, License Number 5010440403768 February 15, 2021.

Supplementary Table 3.2.*Correlations between Low- and High-frequency Hearing Measure and Cognitive Control*

	Low-frequency hearing measure	High-frequency hearing measure
Cognitive Flexibility		
Category Fluency	-.28	.05
COWAT - Letter Fluency	-.06	-.11
TMT-B (s)	.16	.30
Stroop mixing cost	.17	-.26
Inhibitory Control		
Stroop color-word interference (s)	.13	.46*
SC NoGo error (%)	.14	.17
OA NoGo error (%)	.24	.28

Cells represent zero-order correlation coefficients. COWAT = Controlled Oral Word Association Test (Benton & Hamsher, 1976); TMT = Trail Making Test (Reitan, 1958); SC = Single-Car Task; OA = Object-Animal Task.

* $p < .05$

Supplementary Table 3.3.

Correlation after Controlling for Trail Making Test-A

	Binaural QuickSIN score
TMT-B	.57*

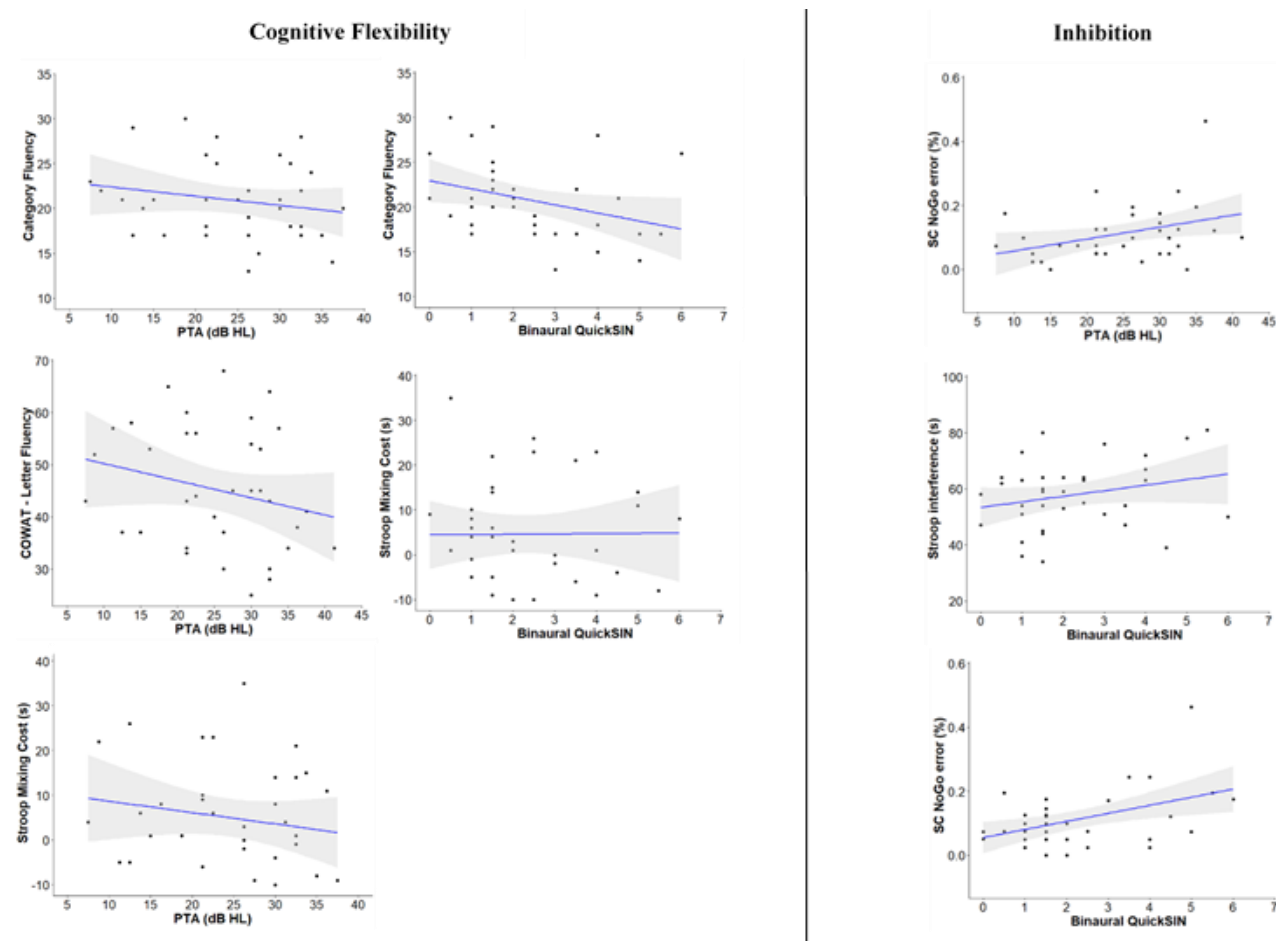
Cell represents partial correlation coefficient after controlling for completion time on TMT-A.

QuickSIN = Quick Speech-in-Noise (Killion et al., 2004); TMT = Trail Making Test (Reitan, 1958).

* $p < .05$

Supplementary Figure 3.1.

Non-Significant Relationships between Hearing and Cognitive Control Variables



PTA (dB HL) = Pure-Tone Average (decibels hearing level); QuickSIN = Quick Speech-in-Noise (Killion et al., 2004); COWAT = Controlled Oral Word Association Test (Benton & Hamsher, 1976) ; SC = Single-Car Task; OA = Object-Animal Task.

Chapter 4. Neurophysiological Alterations in Inhibitory Control in Mild Age-Related Hearing Loss

Abstract

Emerging evidence suggests behavioral alterations in inhibitory control in older adults with mild age-related hearing loss (ARHL). Whether there are underlying alterations in the neurophysiological mechanisms linked to these behavioral changes in inhibitory control remain unexplored. The current study examined event-related potentials (ERPs) and event-related spectral perturbations (ERSPs) linked to two Go/NoGo tasks (Single-Car/Object-Animal) in 17 older adults with unaided mild ARHL and 25 age- and education-matched normal hearing (NH) controls. N2 and P3 ERP components and ERSPs in theta and alpha bands were examined in addition to their association with speech-in-noise (SiN) recognition. Findings revealed different neural patterns of processing linked to NoGo versus Go trials in individuals with ARHL and NH controls. The ARHL group showed longer NoGo N2 latency relative to Go N2 latency on the Single-Car task. The NH group showed higher P3 amplitude and greater alpha desynchronization for NoGo versus Go trials on the Object-Animal task, but this differentiation was lacking in the ARHL group. Additionally, poorer recognition of SiN in the ARHL group was related to higher P3 amplitude on NoGo trials in the Object-Animal task, suggesting that those with worse central hearing were exerting greater neural effort on inhibition trials. These findings add to literature on ARHL and cognition by showing that even mild ARHL alters neural processing underlying inhibitory control.

4.1. Introduction

Inhibitory control is a top-down cognitive control (also known as executive control) process (Campbell et al., 2020; Hasher et al., 1991; Wilkinson & Yang, 2016). It refers to the controlled ability (as opposed to automatic ability) to suppress irrelevant information and responses, including motor responses, in order to attend to relevant information (Campbell et al., 2020; Hasher et al., 1991; Hasher & Zacks, 1988; Houghton & Tipper, 1994; McDowd, 1997). Inhibitory control is engaged in common day-to-day situations. For instance, successfully understanding a conversation partner in a noisy situation such as a restaurant, requires the use of inhibitory control to suppress other background conversations. Like other cognitive functions, inhibitory control develops and improves over childhood, and starts declining during late adulthood (Christ et al., 2001; Williams et al., 1999). It is well established that inhibitory control declines with aging and is exacerbated by the presence of other age-related health conditions (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). A highly prevalent condition in older adults is age-related hearing loss (ARHL), which affects 50% of individuals above 75 years of age (National Institute on Deafness and Other Communication Disorders, 2018). Currently, 430 million people live with hearing loss globally. By 2050, 700 million people will have hearing loss, of which ARHL will be the leading cause (Haile et al., 2021; World Health Organization, 2022).

Growing evidence suggests that ARHL is a modifiable risk factor for dementia and is associated with cognitive alterations (Lin, 2011; Lin et al., 2011a, 2011b, 2013; Livingston et al., 2017; see Powell et al., 2022; Thomson et al., 2017 for reviews). Over the years, numerous studies have reported changes in global cognitive function (Alattar et al., 2020; Loughrey et al., 2018; Sugawara et al., 2011; Yue et al., 2021), speed of processing (Hällgren et al., 2001;

Kestens et al., 2021; Lin et al., 2011a, 2013), and episodic and semantic memory (Brewster et al., 2021; Cutler & Ilinca, 2020; Harvey et al., 2018; Lin et al., 2011a, 2013; Rönnberg et al., 2013; Shahidipour et al., 2013; Uhlmann et al., 1989). There is some evidence to suggest that beyond these cognitive alterations, changes in cognitive control processes occur even in those with mild ARHL (Lin, 2011; Lin et al., 2011a, 2013; Lin, 2011). Our previous studies have demonstrated behavioral alterations in the cognitive control process of inhibitory control in individuals with mild ARHL relative to normal hearing (NH) controls (Shende et al., 2021, 2022). Theoretical propositions suggest that neural changes underlie behavioral deficits (CHABA, 1988; Lindenberger & Baltes, 1994). Thus, the goal of the current study is to examine whether there are underlying alterations in the neurophysiological mechanisms linked to behavioral changes in inhibitory control in individuals with mild ARHL relative to NH controls. First, a brief discussion on aging and inhibitory control will be presented to set the context for discussion on inhibitory control in ARHL.

4.1.1. Inhibitory Control and Aging

The earliest research on inhibitory control in aging can be traced back to experiments conducted by Patrick Rabbitt who examined older and younger adults' ability to ignore distracting information (Rabbitt, 1964, 1965, 1967). In his study, Rabbitt (1965) required participants to sort cards into two separate piles based on whether two letters designated as relevant, "A" or "B" were printed on them. In addition to the two relevant letters, the cards were also printed with letters designated as irrelevant (C-Z). Errors in sorting the letters were recorded. Their findings revealed that older adults made greater errors in sorting and that their sorting times were more susceptible as the amount of irrelevant information increased, in this case, letters C-Z, relative to younger adults. Rabbitt (1965) concluded that older adults have

greater difficulty in ignoring irrelevant information, suggesting aging-related alterations in inhibitory control.

Similar observations of inhibitory control changes with aging by others (see Hasher & Zacks, 1988) propelled further research on the topic. Copious evidence indicates that older adults are impacted by *distracting information more so than younger adults* (Amer & Hasher, 2014; Biss & Hasher, 2011; Earles et al., 1994; Healey et al., 2008; Schneider et al., 2000; Stoltzfus et al., 1993; Tipper, 1991; Weeks & Hasher, 2014). For instance, distracting information disproportionately slowed older adults on the Stroop and Flanker tasks (Connelly et al., 1991; Lustig et al., 2008; Spieler et al., 1996; West & Alain, 2000; Zeef et al., 1996), which require ignoring distracting stimuli to attend to target stimuli. Similarly, older adults attended to trials that were to be ignored more so than younger adults on negative priming experiments (McDowd & Oseas-Kreger, 1991; see Verhaeghen & De Meersman, 1998 for a meta-analysis), indicating deficits in their ability to successfully inhibit goal-irrelevant information.

The increasing evidence on inefficiencies in ignoring distracting, irrelevant information with advanced age led to the seminal “Inhibitory Theory”, also known as the “Inhibitory Deficit hypothesis” put forth by Hasher and Zacks in 1988 (Hasher, 2015; Hasher et al., 1991; Hasher & Zacks, 1988). They proposed that with aging, there is a reduction in the effectiveness of inhibitory mechanisms, which is essential for attending to important information by suppressing irrelevant information. Inhibitory Theory suggests that efficient inhibitory control is necessary to allow only goal-relevant information to enter one’s working memory, i.e., one’s mental workspace (Hasher, 2015; Hasher et al., 1991; Hasher & Zacks, 1988). In 1999, the Inhibitory Theory was updated to delineate the functions of inhibitory control, i.e., **access**, **deletion**, and **restraint** (Hasher et al., 1999). The *access* function operates when information is first presented

and serves as a gatekeeper to limit focus to those mental representations that are relevant to current goals. The *deletion* function operates when active information in one's working memory is either irrelevant or becomes irrelevant as the tasks, goals, and topics change. Finally, the *restraint* function operates to restrain strong responses that are triggered by familiar cues. In other words, the restraint function allows for selection among competing responses by suppressing prepotent or relatively automatic responses in both thought and action.

Behavioral Evidence for Age-Related Declines in Inhibitory Control: Extensive evidence exists on age-related changes in the functions of access, deletion, and restraint related to inhibitory control. Alterations in access function have been found on several tasks, including selective attention, negative priming, distractor interference tasks, and reading tasks (see Lustig et al., 2008). Typically, these tasks require a response to certain stimuli (target) while ignoring distracting stimuli. Numerous studies have shown that older adults attend to irrelevant distractors significantly more than younger adults (see Campbell et al., 2020 for a review; Connelly et al., 1991; McDowd, 1997; Zanesco et al., 2020), indicating alterations in their ability to restrict access to (process) only goal-relevant information. Age-related alterations have been found on tasks of deletion function as well. These tasks include working memory span, garden path sentences, directed forgetting paradigms, and proactive interference, which require determining which unit/item is currently relevant to task performance and discarding items that are no longer relevant. On these tasks, older adults tend to recall more items that are no longer relevant compared to younger adults suggesting reduced ability to delete non-relevant information (D. L. Chiappe & Chiappe, 2007; P. Chiappe et al., 2000; Feyereisen & Charlot, 2008; Lustig et al., 2008; Zeintl et al., 2007).

Of the three functions of inhibitory control, restraint has received the most attention (Lustig et al., 2008). Typically, this function has been examined using response inhibition tasks that require participants to suppress a habitual/prepotent/automatic response, with studies predominantly using the Stop-Signal and Go/NoGo tasks (Lustig et al., 2008; Swick et al., 2011). Briefly, these tasks require participants to respond to certain stimuli (Go trials on Go/NoGo tasks) and withhold responses to others (NoGo trials on Go/NoGo tasks, Stop signal on the Stop-Signal tasks). Decades of research has shown that older adults have difficulties in inhibiting the prepotent responses, as indexed by higher errors or false alarms on inhibitory control trials (trials requiring withholding of response such as NoGo trials on Go/NoGo tasks) compared to younger adults (Hsieh et al., 2016; Kubo-Kawai & Kawai, 2010; Mudar et al., 2015; see Rey-Mermet & Gade, 2018 for a meta-analysis; Vallesi et al., 2011; van de Laar et al., 2011). When taken together, evidence suggests that with aging all three functions of inhibitory control decline, providing extensive support to the Inhibitory Theory.

Despite considerable support, the Inhibitory Theory has received a fair amount of criticism. In 1997, McDowd challenged the Inhibitory Theory and suggested that several components of the theory required further elaboration and modification (McDowd, 1997). A major criticism was that it lacked specification related to how inhibitory processes affect information processing and the mechanisms underlying the inhibitory processes. McDowd (1997) hypothesized that inhibitory control involves multiple mechanisms and suggested that propositions by Houghton and Tipper (1994) could guide the identification of inhibitory control mechanisms. Houghton and Tipper (1994) suggested a “gain control mechanism” for inhibitory control, such that when an information processing system is required to process some target information in the presence of non-target information, the inhibitory control system may

accomplish this by boosting the signal that represents the target information and dampening the signal for the non-target information. This boosting/dampening of signals was hypothesized to occur at the biological level i.e., the *neurophysiological level*.

A technique that has been used to examine the neurophysiological basis of inhibitory control and age-associated changes is electroencephalography (EEG; see Dustman et al., 1993; Falkenstein et al., 2002 for reviews). Event-related EEG, in particular, can tap into real-time neural processing linked to cognitive processes. Studies using event-related EEG to examine neurophysiological alterations in inhibitory control have predominantly used response inhibition tasks which index restraint function. Mainly, the Go/NoGo and Stop-Signal tasks have been widely used. Typically, these EEG data have been analyzed in two ways: event-related potentials (ERPs), which examine the temporal aspect of the EEG signal; and event-related spectral perturbations (ERSPs) or event-related oscillations which examine the frequency/spectral and temporal aspects of the signal (Makeig, 1993; Makeig et al., 2004).

Neurophysiological Evidence for Age-Related Declines in Inhibitory Control: ERP studies using tasks such as the Go/NoGo and Stop-Signal tasks (Falkenstein, 2006; Falkenstein et al., 2002; Kropotov et al., 2016; Mudar et al., 2015) typically elicit an N2 ERP component between 200-400 ms post-stimulus onset over the frontocentral electrode sites and a P3 ERP component over the parietal sites, with both components tied to inhibitory control (Falkenstein et al., 1999; Kok, 1999; Pfefferbaum et al., 1985; Pfefferbaum & Ford, 1988). These studies have shown that older adults have longer N2 and P3 latencies relative to younger adults (Cheng et al., 2019; Johnstone et al., 2005; Kropotov et al., 2016; Mudar et al., 2015; Vallesi et al., 2011). The amplitude data has been more variable but has shown differences between older and younger

adults (see Cheng et al., 2019 for meta-analysis; Pfefferbaum & Ford, 1988; Vallesi et al., 2011), indicating age-related neural alterations in inhibitory control.

The ERSP studies on inhibitory control have typically examined neural oscillations in theta (4-7 Hz), low-frequency alpha (8-10 Hz), high-frequency alpha (11-13 Hz), and beta (12-30 Hz) bands (Buzsáki & Watson, 2012; Ishii et al., 2018; Klimesch et al., 2007). Typically, these studies have examined peak or mean spectral power with some exceptions (Papenberg et al., 2013; Schmiedt-Fehr et al., 2009). Changes in spectral power are commonly discussed in terms of event-related synchronization (ERS) and event-related desynchronization (ERD), which refer to event-related spectral power increases or decreases relative to a baseline period, respectively (for a review, see Pfurtscheller & Lopes da Silva, 1999).

ERSP studies that have examined age-related declines in inhibitory control using the Go/NoGo and Stop-Signal tasks have observed alterations in theta/alpha bands. Specifically, studies have found lower ERS in the theta band (Cohen & Donner, 2013; Huizeling et al., 2020; Nigbur et al., 2011) and lower ERD in the alpha bands (Borghini et al., 2018; Nombela et al., 2014; Schmiedt-Fehr et al., 2009) on inhibition trials in older adults compared to younger adults. Taken together, ample evidence for neurophysiological alterations in inhibitory control with aging have been gathered from ERPs and ERSPs, however much remains to be understood as to how this relates to the gain control mechanism of inhibitory control.

4.1.2. Inhibitory Control Changes with ARHL

The previous section described inhibitory control alterations that occur with aging, at behavioral and neurophysiological levels. One of the most prevalent conditions in older adults is ARHL, and emerging evidence suggests alterations in inhibitory control in this population that

may go beyond the typical aging-related changes. This section will focus on existing work on inhibitory control in ARHL and gaps in research, leading to the aims of the current study.

Behavioral Changes in Inhibitory Control in ARHL: Inhibitory control in older adults with ARHL has been mostly examined using the Stroop task, (Guerreiro & Van Gerven, 2017; Janse, 2012; Knight & Heinrich, 2017, 2019; Lin et al., 2011a), except for van Knijff et al. (2018) who used the Simon task. Briefly, the Stroop task requires inhibiting reading color names to say the ink in which color names are written (for e.g., say “red” for color name green written in red ink). Overall, findings from these studies have been inconclusive. Some have reported inhibitory control deficits in individuals with mild (Guerreiro & Van Gerven, 2017; Ren et al., 2019) to severe (Lin et al., 2011) ARHL compared to NH controls, whereas others have not found similar deficits (Harrison Bush et al., 2015; Huber et al., 2020). In a study completed as part of this dissertation work (Chapter 3), we examined inhibitory control in individuals with unaided mild ARHL using the Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001) Stroop task and two Go/NoGo tasks (Maguire et al., 2009). We found that older adults with ARHL had longer completion times on the color-word interference condition of the Stroop task and higher false alarm rates on NoGo trials on the two Go/NoGo tasks compared to age-matched NH controls (Shende et al., 2021). Our findings indicate slower as well as worse inhibitory control in mild ARHL, providing support for inhibitory control alterations even in individuals who have milder degrees of hearing loss. Given that our ARHL and NH groups were age-matched, these inhibitory control alterations in individuals with ARHL appear to go beyond typical aging-related declines. Also, studies have shown that alterations in inhibitory control affects one’s ability to suppress irrelevant background noise in complex listening situations, and thus, might play a role in the commonly reported issue of speech-in-noise (SiN) recognition in

older adults (Janse, 2012; Knight & Heinrich, 2017, 2019; van Knijff et al., 2018). Indeed, our work has found a relationship between SiN recognition and inhibitory control, such that poorer sentence recognition in noise on the Quick Speech-in-Noise (QuickSiN) task was associated with higher false alarm rates on NoGo trials, i.e., worse inhibitory control (Shende et al., 2021). However, what remains unknown is whether there are underlying alterations in the neurophysiological mechanisms linked to behavioral changes in inhibitory control beyond what is observed as a result of normal aging in older adults with ARHL.

Theoretical postulations linking hearing loss and cognition suggest underlying neural changes in individuals with ARHL. The common-cause hypothesis suggests that a common factor, neurodegeneration due to aging, leads to both ARHL and cognitive changes and thus, links the two. Two other hypotheses, the information-degradation hypothesis (CHABA, 1988; Schneider & Pichora-Fuller, 2000) and the sensory-deprivation hypothesis (Baltes & Lindenberger, 1997; CHABA, 1988; Oster, 1976) suggest that hearing loss can lead to cognitive changes. Specifically, they suggest that the limited, modality-general neural resources in ARHL get recruited to aid auditory activities often to the detriment of other cognitive activities, including those involving inhibitory control. These cognitive changes have been posited to be reversible according to the information-degradation hypothesis, or irreversible by the sensory-deprivation hypothesis. Examining neurophysiological changes underlying inhibitory control using event-related EEG would provide some initial insights into the neural mechanisms that underlie changes in inhibitory control in ARHL.

EEG studies in ARHL have mostly examined ERPs. Auditory-evoked ERPs (such as auditory brainstem response, mid-latency response, and long-latency response) have been used to examine neural processing linked to perceptual processing of auditory stimuli (Key, 2016;

Khullar & Babbar, 2011; Kırkım et al., 2007; Konrad-Martin et al., 2012; Matas et al., 2006; Rosenhall et al., 1986). A handful of studies in ARHL (Billings et al., 2015; Giroud et al., 2017; Oates et al., 2002) have used the oddball paradigm to examine the ability to strategically attend and respond to stimuli with pre-defined speech characteristics. Typically, oddball paradigms involve the presentation of two types of stimuli, one frequently occurring standard stimulus (e.g., a phoneme /ba/) and another infrequent deviant stimulus (e.g., /da/). Participants are asked to attend to and respond to the infrequent deviant stimuli. Overall, longer latency and reduced amplitude for N1, N2, and P3 ERP components have been observed in those with mild ranging to moderate (Giroud et al., 2017) and severe (Oates et al., 2002) ARHL relative to NH older adults even when stimuli were presented at suprathreshold levels. To the best of our knowledge, no studies have specifically examined ERPs linked to inhibitory control in this population.

Relative to ERPs, examination of ERSPs in ARHL has received even less attention with only two studies conducted so far (Petersen et al., 2015; Price et al., 2019) to the best of our knowledge. Price et al. (2019) examined ERSPs in relation to a SiN task in older adults with NH and mild ARHL and found that poorer SiN perception was associated with higher phase coherence in the alpha frequency band (8-12 Hz). The second study examined ERSPs in relation to an auditory working memory task in which stimuli were presented in background noise (Petersen et al., 2015) to older adults with mild-to-moderate ARHL and NH. Participants were asked to hear a list of digits (study items), followed by a single digit (test item), and asked to judge if the test item belonged to the list of study items. They found higher alpha power under high working memory load (when participants had to retain more study items) and high levels of background noise in individuals with moderate ARHL relative to NH individuals. These findings suggest that activity in the alpha band is influenced by the degree of ARHL, background noise,

and complexity of working memory task. To the best of our knowledge, no studies have examined ERSP alterations underlying inhibitory control in individuals with ARHL.

Given the paucity of studies examining event-related EEG studies linked to inhibitory control in individuals with ARHL, the goal of this study was to examine ERPs and ERSPs in individuals with mild ARHL relative to age- and education-matched NH controls using the classic Go/NoGo paradigm. We decided to focus on the unaided mild ARHL group to understand whether mild alterations in hearing, which typically goes untreated, impacts inhibitory control. We intentionally chose to use a visual Go/NoGo paradigm to minimize any confounds related to unaided hearing loss. Our **primary research question** aimed to examine differences in measures of ERPs and ERSPs corresponding to Go/NoGo tasks between older adults with mild ARHL relative to age- and education-matched NH controls. We hypothesized that the mild ARHL group would show longer latencies and lower amplitudes on ERPs and lower mean power in ERSPs (ERS in theta band, ERD in alpha bands) compared to the NH group. Given the evidence linking SiN recognition to inhibitory control changes (Janse, 2012; Knight & Heinrich, 2017, 2019), our **secondary research question** aimed to examine if there are associations between central hearing measures and measures of ERPs and ERSPs corresponding to Go/NoGo tasks. We hypothesized that poor central hearing (worse SiN recognition) would be related to ERP/ERSP measures that indicate worse performance on inhibitory control (longer latency/amplitude on ERPs; less ERS/ERD on ERSPs).

4.2. Materials and Methods

4.2.1. Participants

Participants included 17 older adults with unaided mild ARHL (13 female; mean age: 67.18 ± 7.26 years; mean education: 17.82 ± 3.48 years) and 25 age- and education-matched NH

controls (17 female; mean age: 66.04 ± 7.05 years; mean education: 17.20 ± 2.30 years). With the exception of four participants in the NH group, all participants in this study were also part of study two (Chapter 3) of this dissertation. Demographic information for both groups is reported in **Table 4.1**. All participants were right-handed, native English speakers, and had normal or corrected vision with no history of learning disabilities, psychiatric disorders, neurological disorders, communication disorders, or traumatic brain injury. Individuals with a history of substance abuse, use of psychoactive medications, known etiologies of hearing loss, such as noise-induced, injury-related, or ototoxicity, and those with unilateral and/or bilateral continuous tinnitus, history of hearing aid use, and major vision problems (untreated cataracts, macular degeneration, glaucoma, retinopathy) were excluded.

Participants completed the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), a global cognitive screening measure, which was used to rule out individuals with possible cognitive impairment (cut-off score for exclusion: < 26) and the Geriatric Depression Scale (GDS; Almeida & Almeida, 1999) to rule out those with depressive symptoms (cut-off score for exclusion: > 5). All participants signed a written informed consent in accordance with protocol 17067 approved by the Institutional Review Board of the University of Illinois Urbana-Champaign before completing the study.

4.2.2. Audiological Evaluation

All participants underwent a comprehensive audiological assessment. Assessments included otoscopic evaluation to rule out the presence of outer ear diseases, tympanometry to rule out middle ear dysfunctions, reflexometry to rule out reflex pathway abnormalities, and pure-tone and speech audiometry. Pure tone audiometry was conducted in a sound-treated booth. Air conduction thresholds in each ear were obtained from 0.25 to 8 kHz with insert earphones as

transducers using Equinox 2.0 audiometer calibrated to the American National Standards Institute S3.6 2010 standards (ANSI, 2010). Bone conduction thresholds were obtained from 0.25 to 4 kHz with a bone conduction transducer. All thresholds were determined using the modified Hughson-Westlake method (Carhart & Jerger, 1959) and were measured in decibels hearing level (dB HL). A speech-frequency pure-tone average (PTA) was calculated for air conduction thresholds at 0.5, 1, 2, and 4 kHz in each ear. Based on extant literature, NH was defined as ≤ 25 dB HL PTA in the better ear and ARHL was defined as > 25 dB HL PTA in the better ear (Lin et al., 2011a, 2013). PTA score in the better ear was used as a measure of peripheral hearing. See **Figure. 4.1** for audiograms for both ARHL and NH groups.

Speech audiometry was conducted using insert ear transducers, including Speech Reception Thresholds (SRTs) using spondee words, and Word Recognition Score (WRS) using the Northwestern University list 6 (Tillman & Carhart, 1966) in each ear. SRTs and WRS scores were obtained to determine the adequate presentation level for the administration of the SiN test of interest, the Quick Speech-in-Noise test (QuickSIN; Killion et al., 2004). The QuickSIN test was administered in right, left, and both (binaural) ears at 70 dB HL for all participants, as recommended (Killion et al., 2004), except for two in the ARHL group. For these two participants QuickSIN test was administered at their most comfortable levels (75 dB HL and 80 dB HL), since they perceived speech stimuli presented at 70 dB HL as comfortable but soft. The QuickSIN task required participants to repeat back sentences presented against multi-talker babble at signal-to-noise ratios that varied in 5 dB steps from +25 dB to 0 dB. QuickSIN scores were recorded, with higher scores suggesting worse SiN recognition. Binaural QuickSIN score was used as a measure of central hearing. Binaural scores were chosen as they represent the functional performance of using both ears in daily complex listening tasks.

4.2.3. EEG Task

All participants completed two experimental visual Go/NoGo inhibitory control tasks, the “Single-Car” task that requires basic categorization and the “Object-Animal” task that requires superordinate categorization, with the latter being the more complex requiring careful evaluation of both perceptual and semantic features of stimuli. Both the Single-Car and the Object-Animal task consisted of 200 stimuli that were black and white line drawings fitted to a white 600 x 600 pixel square. Of these 200 trials, 160 trials (80%) were Go trials and 40 trials (20%) were on NoGo trials. This trial distribution was used to emphasize the tendency for a pre-potent response. Each stimulus was presented for 300 ms followed by a 1,700 ms fixation period (with a “+” presented in the center of the display). These tasks were developed by Maguire et al. (2009), with the intent of examining how inhibitory control and semantic complexity interact with each other; and have been successfully used in several studies involving older adults (Brier et al., 2010; Chiang et al., 2013; Mudar et al., 2015, 2016).

The Single-Car task consisted of 160 line-drawn exemplars of one car (Go trials) and 40 line-drawn exemplars of one dog (NoGo trials) that were shown on a computer screen. Participants were required to make quick and accurate Go/NoGo decisions, where a button push response was required for car (Go) but not for dog (NoGo). This task involves basic visual categorization of objects, which largely depends on perceptual processing of stimuli. They were given the following instructions on the computer screen before beginning the task: “You are going to see some dogs and cars. When you see a dog, do not push the button. Press the button for anything that is not a dog. Be as quick and as accurate as possible”.

The Object-Animal task consisted of 160 line-drawn exemplars of multiple objects (Go trials) and 40 line-drawn exemplars of multiple animals (NoGo trials) that were shown on a

computer screen. Exemplars of objects consisted of 40 food items, 40 cars, 20 clothing items, 20 kitchen items, 20 human body parts, and 20 tools, and exemplars of animals consisted of items with varying visual typicality, such as cat, snake, elephant, and lobster. Participants were asked to make quick and accurate Go/NoGo decisions, where a button push was required for objects (Go) but not for animals (NoGo). This task involves superordinate visual categorization of objects, which engages both perceptual and semantic processing. The following instructions were presented: “You are going to see some objects and animals. When you see an animal, do not push the button. Press the button for anything that is not an animal. Be as quick and accurate as possible.”

Order and practice effects were minimized by pseudo-randomization of the sequence of stimuli in each task, and task order was counterbalanced for each participant. Together, both tasks took seven minutes for completion. For each task, a Compumedics NeuroScan Stim System Switch response pad (button-box) was used to register Go responses and record reaction times. Additionally, accuracy was calculated for Go and NoGo responses for each task. See **Figure 4.2** for stimulus exemplars of Single-Car and Object-Animal Tasks.

4.2.4. EEG Data Acquisition and Processing

Continuous EEG was recorded while participants performed the two Go/NoGo tasks, using a 64-electrode Neuroscan Quik-Cap, Neuroscan SynAmps RT amplifier, and Scan v4.5 software (sampling rate: 1 kHz, DC-200 Hz). Electrode impedances were typically kept below 10 k Ω to minimize any decrease in signal-to-noise ratio. The reference electrode was located at the midline between Cz and CPz electrodes. Vertical electrooculogram (VEOG) was recorded by placing electrodes below and above the left orbit of the eye to monitor for movements and eye blinks. The amplifier was set at bandpass filtering of 0.1 Hz – 100 Hz. The raw EEG data were

processed offline to correct for eye blinks and muscular artifacts using the Neuroscan Edit software. Poorly functioning electrodes were identified by visual inspection and excluded from analysis. The continuous EEG data were high-pass filtered at 0.15 Hz and corrected for eye blinks using spatial filtering.

The EEG data were epoched from -500 ms before stimulus onset to 1500 ms after presentation of the stimulus. Epochs with peak signal amplitudes of more than 75 μ V were rejected. The rejection rates for ARHL/NH groups for ERPs were 0.13%/0.16% for Go trials and 0.13%/0.17% for NoGo trials in the Single-Car task, 0.12%/0.15% for Go trials and 0.13%/0.15% in NoGo trials for the Object-Animal task. For ERSPs, the rejection rates for ARHL/NH groups were 0.12%/0.13% for Go trials and 0.12%/0.15% for NoGo trials in the Single-Car task and 0.12%/0.14% for Go trials and 0.13%/0.15% for NoGo trials in the Object-Animal task. There were no significant differences in the rejection rates between groups across trial types in both tasks for ERPs (Go/NoGo trials for Single-Car task: $p = .409/.253$; Go/NoGo trials for Object-Animal task: $p = .378/.455$) and ERSPs (Go/NoGo trials for Single-Car task: $p = .902/.456$; Go/NoGo trials for Object-Animal task: $p = .560/.578$). Only correct trials, i.e., trials to which the participant responded correctly, were included in the analysis. The EEG data were re-referenced to the average potential over the entire scalp. Following this step, further analyses to obtain ERPs and ERSPs differed, the details of which are outlined below.

4.2.5. ERP Analyses

Following the preprocessing of the EEG data, baseline correction was done by subtracting the mean amplitude of the pre-stimulus interval (-500 to 0 ms) from each time point in Neuroscan Edit. An algorithm computing the average based on spherical splines fitted to the data was then applied to interpolate EEG data to the sites of the bad electrodes. Individual ERP

data time-locked to the Go and NoGo trials were then averaged for the Single-Car and the Object-Animal tasks separately. Only correct trials were included in the ERP averages. Visual inspection of the ERP waveforms revealed typical ERPs, including N2 and P3 ERP components, in both the ARHL and NH groups. We focused on N2 and P3 components, which are typically linked to Go/NoGo tasks, in the midline and para midline electrodes. We measured peak latency and mean (area) amplitude for each group between 150 and 300 ms for N2 at six midline electrodes (F1, Fz, F2, FC1, FCz, FC2) and between 250 and 600 ms for P3 at 9 midline electrodes (FC1, FCz, FC2, C1, Cz, C2, CP1, CPz, CP2) for Go and NoGo trials (see **Figure 4.3**). Peak latency and mean amplitude were derived by using a Tcl Batch command script in Neuroscan Edit. Thus, no observer bias was present in selection of N2 and P3 peak latencies and mean amplitudes.

The electrode sites and time windows were selected based on i) previous N2/P3 studies, in particular, studies from our group that have successfully used this task in cognitively healthy younger and older adults (Brier et al., 2010; Chiang et al., 2013; Maguire et al., 2009, 2010; Mudar et al., 2015), and ii) the consistency with which N2 and P3 ERPs were observed across participants at each electrode location. We averaged peak latency and mean amplitude across the six electrodes in the frontal and fronto-central scalp regions to examine N2 and across the nine electrodes in the fronto-central, central, and centro-parietal scalp regions for examining P3.

4.2.6. ERSP Analyses

ERSPs were extracted with time-frequency analysis using the EEGLAB toolbox (Delorme & Makeig, 2004) running under Matlab 2016b (MathWorks, Natick, MA, USA) for each group (ARHL/NH) across tasks (Single-Car, Object-Animal) and trial types (Go/NoGo) for correct trials only. Time-frequency analysis was performed at five electrode clusters, with each

electrode cluster being an average of midline and para-midline electrodes (frontal: F1, Fz, F2; fronto-central: FC1, FCz, FC2; central: C1, Cz, C2; centro-parietal: CP1, CPz, CP2; parietal: P1, Pz, P2; **see Figure 4.4**). These electrode clusters were selected based on three of our previous studies that have examined ERSPs using these Go/NoGo tasks (Lydon et al., 2022; Mudar et al., 2019; Nguyen et al., 2017). Two of these studies (Mudar et al., 2019; Nguyen et al., 2017) did not examine ERSPs at the frontocentral and centro-parietal sites. However, we included these electrode clusters for improved sampling of the EEG data and to gain a more comprehensive picture of neural activity across anterior-posterior sites, especially given that this study is the first to examine ERSPs underlying inhibitory control in older adults with ARHL.

Epochs for each trial type were divided into 200-time points between -372 and 1372 ms. Mean spectral power was calculated at each time point using a sliding window of 256 ms with a step-size of 10 ms and a pad ratio of 4, which resulted in a frequency resolution of approximately 1 Hz, with power estimated at 48 linear-spaced frequencies from 4–50 Hz. Each sub-window was short-time Fourier transformed with Hanning window tapering as implemented in the EEGLAB function *newtimef.m*. Baseline correction was completed in accordance with the gain model (Delorme & Makeig, 2004; Grandchamp & Delorme, 2011), in which power at each time-frequency point was divided by the average pre-stimulus baseline power at the corresponding frequency. The resulting spectral power at each of the 48 frequencies and 200 time points were averaged across all epochs within each trial type for each group. We focused on examining ERSPs within the theta (4-7 Hz), low-frequency alpha (8-10 Hz), and high-frequency alpha (11-13 Hz) bands across the five electrode clusters. We chose theta and alpha bands given that inhibitory control has been associated with activity in these brain rhythms (Ishii et al., 2018; Klimesch, 1996, 1999; Klimesch et al., 1994; Nombela et al., 2014; Yamanaka & Yamamoto,

2010), including our previous studies that have used the same Go/NoGo tasks (Lydon et al., 2022; Mudar et al., 2019; Nguyen et al., 2017).

ERSP analyses were conducted between two time-windows, 150-300 ms and 300-650 ms. These two time-windows were chosen based on i) visual inspection of spectrograms depicting ERSPs for each of the groups (ARHL/NH) across tasks and trial types, ii) our previous studies that have used similar time windows (Lydon et al., 2022; Nguyen et al., 2017), and iii) consistency of these time periods to the time frame of N2 and P3 components typically elicited in Go/NoGo paradigms. With regard to alpha band, we first calculated individual alpha frequency (IAF) for each participant to examine if there are group differences. IAF was determined using the method outlined in Klimesch et al. (1999) by identifying which frequency had peak power across an extended alpha range (7–14 Hz). No significant difference in IAF was observed between the ARHL and NH groups in the Single-Car task (Go: ARHL = 10.41 ± 2.70 , NH = 9.14 ± 1.95 , $p = .09$; NoGo: ARHL = 10.09 ± 2.20 , NH = 9.45 ± 2.08 , $p = .365$), and the Object-Animal task (Go: ARHL = 9.93 ± 2.42 , NH = 9.21 ± 2.01 , $p = .302$; NoGo: ARHL = 10.22 ± 2.58 , NH = 9.80 ± 2.21 , $p = .575$), so we used the fixed range as has been used in other studies (8-10 Hz for low-frequency alpha; 11-13 Hz for high-frequency alpha). As opposed to the full alpha band (8-12 Hz), we estimated low-frequency and high-frequency alpha bands separately given that studies have found differences in these two bands when tasks with varying semantic complexity, (Klimesch, 2012; Klimesch et al., 1994, 2007), which is the case with the Single-Car and the Object-Animal tasks, are used.

Our previous work analyzing ERSPs during this task has shown that following stimulus onset, theta band power is consistently more positive relative to baseline, capturing ERS, i.e., event-related synchronization (see introduction section 4.1.1. for explanation on ERS and ERD);

while alpha band power is consistently more negative relative to baseline, thereby capturing ERD, i.e., event-related desynchronization. Thus, we focused our analysis on ERS in the theta band and ERD in the alpha band.

4.2.7. Statistical Analyses

Statistical analyses were done using IBM SPSS Statistics Version 26. Visual inspection of histograms with normal curves and qqplots was conducted to ascertain whether demographic variables, participant characterization (MoCA; GDS) measures, audiological variables, and measures of behavioral data of the Go/NoGo tasks were normally distributed for each group (ARHL/NH). Visual inspection of these variables revealed normal distribution, following which parametric statistics were used to conduct further analyses. Given that our event-related EEG data were normalized during preprocessing and that parametric statistics have been shown to be valid and robust to deviations from normality for event-related EEG data (Alday, 2019; Kiebel et al., 2005), we used parametric statistics for analyses of our ERP and ERSP data as well.

General Linear Models (GLMs) were used to first examine group (ARHL/NH) differences in demographic variables, participant characterization measures and audiological variables. To address the primary research question, separate GLMs were used for the Single-Car and Object-Animal task to examine behavioral data (accuracy), ERP data (peak latency and mean amplitude for N2, P3 ERP components), ERSP data (theta ERS and alpha ERD). The GLMs included group (ARHL/NH) as a between-subject factor and trial type (Go/NoGo) as a within-subject factor. Given that reaction times could only be extracted for Go trials, the reaction time data were evaluated with an independent samples t-test. Alpha was fixed at 0.05, and in the case of significant group by trial interactions, post hoc comparisons were carried out. Bonferroni corrections were used to correct for multiple comparisons.

Pearson's correlations were conducted to examine associations between central hearing and neural measures of inhibitory control for the whole group and for ARHL and NH groups individually. Given that central hearing is closely related to peripheral hearing, we conducted partial correlations between central hearing and ERP and ERSP measures of inhibitory control, while controlling for peripheral hearing ability. Our correlational analyses were guided by the findings of the primary research question to reduce the burden of multiple correlational tests. Thus, we conducted correlations of central hearing with only those neural measures of inhibitory control in which significant effects were observed, either in terms of main effects of group and/or interactions between group and trial type. All correlational analyses were conducted after dropping outliers ± 2 standard deviations from the mean score of the variables being assessed.

4.3. Results

4.3.1. Demographics and Characterization Variables

Group means for demographic and participant characterization variables are reported in **Table 4.1**. Groups were comparable for age, education, and sex. Additionally, groups did not differ on other characterization measures, including MoCA scores and GDS scores.

4.3.2. Group Differences

4.3.2.1. Audiological Data

Group means for audiological data are reported in **Table 4.2**. Main effects of group were observed for the audiological variables of interest: PTA, $F(1,40) = 72.368$, $p < .001$, $\eta^2 = .644$ and binaural QuickSIN score, $F(1,40) = 7.447$, $p = .009$, $\eta^2 = .157$, with higher PTA and binaural scores in ARHL compared to the NH group. Group differences were also observed on audiological characterization measures, right ear SRT, $F(1,40) = 23.315$, $p < .001$, $\eta^2 = .368$; left ear SRT, $F(1,40) = 48.019$, $p < .001$, $\eta^2 = .546$; right ear WRS, $F(1,40) = 5.349$, $p = .026$, $\eta^2 =$

.118; and left ear WRS, $F(1,40) = 4.372$, $p = .043$, $\eta^2 = .099$. Significantly higher SRT and lower WRS in both ears were observed in the ARHL relative to NH group.

4.3.2.2. Go/NoGo Behavioral Data

Group means for reaction time for the Go trials and accuracy for the Go and NoGo trials are reported in **Table 4.3** and statistical results of behavioral task performance are reported in **Table 4.4**. A significant main effect of trial type was observed for accuracy on the Single-Car task, $F(1,38) = 9.292$, $p = .004$, $\eta^2 = .196$, with higher accuracy for Go relative to NoGo trials. However, a significant group by trial interaction was also observed for accuracy on the Single-Car task, $F(1,38) = 5.972$, $p = .019$, $\eta^2 = .136$. Post hoc tests revealed significant differences between trial types within the ARHL group, with higher accuracy for the Go trials relative to NoGo trials, $t(14) = 6.626$, $p < .001$, $d = 1.711$. There was no significant difference between trial types within the NH group, as well as no between group effects. Additionally, no significant group differences were observed for reaction time on the Single-Car task. With regard to the Object-Animal Task, a significant main effect of trial type was observed for accuracy, $F(1,38) = 6.763$, $p = .013$, $\eta^2 = .145$, with higher accuracy for Go relative to NoGo trials. No other significant effects were observed for accuracy or reaction time measures.

4.3.2.3. Go/NoGo ERP Data

Group means for ERP measures are reported in **Table 4.5**, and statistical results for ERP measures are reported in **Table 4.6**. Grand average ERPs for groups are presented in **Figures 4.5 and 4.6** for the Single-Car task, and **Figures 4.7 and 4.8** for the Object-Animal task. Results below are organized according to the two ERP components that were examined.

N2 ERP component: A significant main effect of trial type was observed for N2 peak latency on the Single-Car task, $F(1,38) = 9.528$, $p = .004$, $\eta^2 = .200$, with longer latency on

NoGo relative to Go trials. However, this main effect was qualified by an interaction. A significant group by trial interaction effect was also observed for N2 peak latency on the Single-Car Task, $F(1,38) = 10.363, p = .002, \eta^2 = .219$. Post hoc tests revealed significant differences between trial types within the ARHL group, with longer latency on the NoGo trials compared to the Go trials, $t(14) = -3.205, p = .006, d = 0.827$. No other effects were significant for peak latency. Also, no differences were observed in N2 mean amplitude on the Single-Car Task. On the Object-Animal task, a significant main effect of trial type was observed for N2 peak latency, $F(1,38) = 5.667, p = .022, \eta^2 = .124$, with prolonged latency on NoGo relative to Go trials. No other effects were observed for N2 peak latency and mean amplitude on the Object-Animal task.

P3 ERP component: A significant main effect of trial type was observed for P3 mean amplitude on the Object-Animal task, $F(1,40) = 4.645, p = .037, \eta^2 = .104$, with higher amplitude on NoGo relative to Go trials. However, this was qualified by a significant group by trial interaction effect, $F(1,40) = 4.881, p = .033, \eta^2 = .109$. Post hoc tests revealed significant differences between trial types within the NH group, with higher amplitude for NoGo trials compared to the Go trials, $t(24) = -4.171, p < .001, d = .834$. No other effects were significant for mean amplitude. Also, no differences were observed in P3 latency on the Object-Animal task, P3 latency and P3 mean amplitude on the Single-Car task.

4.3.2.4. Go/NoGo ERSP Data

Group means for ERS in theta band are shown in **Table 4.7**, for ERD in low-frequency alpha band are shown in **Table 4.8**, and ERD in high-frequency alpha band are shown in **Table 4.9**. Statistical results for ERS in theta band, ERD in low-frequency and high-frequency alpha bands are shown in **Tables 4.10, 4.11, and 4.12** respectively.

Theta band (4-7 Hz): Significant main effect of trial type was observed for ERS in theta band across all electrode clusters between 150-300 ms and between 300-650 ms in the central electrode cluster on the Single Car task. This effect was also observed on the Object-Animal task between 150-300 ms at all electrode clusters except frontal cluster, and between 300-650 ms at frontal and central clusters. See **Table 4.10** for *F*-values, *p*-values and effect sizes. On both tasks, findings revealed greater theta ERS on NoGo relative to Go trials. No significant main effect of group or interaction effect between group and trial type were observed for ERS in the theta band.

Low-Frequency alpha band (8-10 Hz): Significant main effect of trial type was observed for ERD in low-frequency alpha band across all electrode clusters between 150-300 ms and between 300-650 on both the Single Car and the Object-Animal task. See **Table 4.11** for *F*-values, *p*-values and effect sizes. Findings revealed greater ERD on NoGo relative to Go trials. No significant main effect of group or interaction effect between group and trial type were observed for ERD in the low-frequency alpha band.

High-Frequency alpha band (11-13 Hz): A significant main effect of trial type was observed for ERD in high-frequency alpha band at parietal electrode between 150-300 ms in the Single-Car task; and at frontal, frontocentral, central, and centroparietal electrodes between 300-650 ms on the same task. A main effect of trial type was also observed across all electrodes between 300-650 ms on the Object-Animal task, as well as between 150-300 ms in the frontocentral electrode cluster. See **Table 4.12** for *F*-values, *p*-values and effect sizes for main effect of trial type. On both tasks, findings revealed greater ERD in the high-frequency alpha band on NoGo relative to Go trials. In addition to main effects of trial, a significant group by trial interaction effect was observed for high-frequency alpha ERD from 300-650 ms post-stimulus onset in the frontocentral electrode cluster on the Single-Car task, $F(1,38) = 6.008$, $p = .019$, $\eta^2 =$

.137. See **Figure 4.9** for spectrograms. Post hoc tests revealed significant differences between trial types within the NH group, with greater ERD on NoGo trials compared to the Go trials, $t(24) = 4.919, p < .001, d = .984$. In the Object-Animal task, a significant group by trial interaction effect was observed for high-frequency alpha ERD from 300-650 ms post-stimulus onset in the central electrode cluster, $F(1,40) = 10.683, p = .002, \eta^2 = .211$. See **Figure 4.10** for spectrograms. Post hoc tests revealed significant differences between trial types within the NH group, with greater ERD on NoGo trials compared to the Go trials, $t(24) = 6.715, p < .001, d = 1.343$.

4.3.3. Correlations

Correlations between SiN recognition and ERP measures: Informed by interaction effects observed in the ERP measures, we examined correlations between i) binaural QuickSIN score and N2 peak latency on the Single-Car task, and ii) binaural QuickSIN score and P3 mean amplitude on the Object-Animal task. A significant positive association was observed between binaural QuickSIN score and P3 mean amplitude on the NoGo trials within the ARHL group, $r(14) = 0.520, p = .039$. See **Figures. 4.11** for partial correlation plot. No other associations were significant.

Correlations between SiN recognition and ERSP measures: Informed by interaction effects observed in the ERSP measures, we examined correlations between binaural QuickSIN score and ERD in high-frequency alpha (11-13 Hz) in frontocentral electrode between 300-650 ms in the Single-Car task, and in central electrode between 300-650 ms in the Object-Animal task. No significant associations were observed.

4.4. Discussion

The current study investigated changes in inhibitory control in older adults with unaided mild ARHL and NH controls by examining ERPs and ERSPs linked to two Go/NoGo tasks (Single-Car and Object-Animal). Additionally, the associations between central hearing and inhibitory control were examined. Results related to significant group by trial interactions revealed that: (i) the ARHL group had lower accuracy and longer N2 latency on NoGo relative to Go trials on the Single-Car task, and (ii) the NH controls had higher P3 ERP amplitude and greater alpha ERD in high-frequency alpha band on NoGo relative to Go trials on the Object-Animal task. Additionally, a significant positive association was found in the ARHL group between binaural QuickSIN score and P3 amplitude on the NoGo trials in the Object-Animal task.

Before main findings are discussed, it is important to note that the ARHL group showed several typical patterns of behavioral and neural response across the Go and NoGo trials. Similar to the NH group, the ARHL group performed worse, i.e., had lower accuracy on the NoGo relative to Go trials, in the Object-Animal task. This difference in performance across trial types was not surprising given that both our tasks were designed to enhance the tendency for prepotent responses and increase the demand for inhibitory control using unequal distribution of trial types. Also, ERP and ERSP markers linked to Go/NoGo trials in ARHL group showed characteristic trial effects similar to the NH group. Longer N2 latency, greater ERS in theta band, and greater ERD in high-frequency alpha band were observed on NoGo relative to Go trials in both groups. As expected, these findings indicate that processing infrequent NoGo trials to withhold behavioral responses engages more neural resources compared to Go trials in both groups. Also, longer N2 latency on NoGo trials was observed only on the Object-Animal task. It is possible

that our participants took longer to process the NoGo trials on the Object-Animal task owing to the relatively complex nature of this task. This task is more complex than the Single-Car task, given that it requires perceptual and semantic processing and includes multiple exemplars of objects and animals. These differences across trial types observed in the ARHL group similar to the NH group on behavioral and electrophysiological measures align with other studies that have used Go/NoGo tasks with unequal distribution (Eimer, 1993; Falkenstein et al., 1995; Hirose et al., 2012; Vallesi et al., 2011), and have used the same tasks as the current study (Brier et al., 2010; Chiang et al., 2013; Lydon et al., 2022; Maguire et al., 2011; Mudar et al., 2015).

Despite similarities between the ARHL and NH groups, several differences across groups were observed on behavioral, ERP and ERSP data. Behaviorally, a group by trial interaction effect on the Single-Car task showed that older adults with ARHL performed worse i.e., had lower accuracy on the NoGo (0.88%) relative to Go (0.98%) trials. In contrast, NH controls had comparable accuracy across trial types (0.92% on NoGo trials; 0.93% on Go trials). These findings suggest that ARHL group had difficulties in suppressing/inhibiting their responses on the infrequent NoGo trials accurately, indicating impaired inhibitory control. These alterations were observed only on the Single-Car task, which heavily depends on perceptual processing of two line-drawn exemplars of a car and a dog to make basic categorization decisions. Perhaps the repetition of two exemplars in the Single-Car task compared to the 200 exemplars in the Object-Animal task requires more sustained attention to monitor the infrequent NoGo stimuli, resulting in more errors. These changes in inhibitory control tied to perceptual processing are consistent with other studies that have shown alterations in inhibitory control on Stroop and Simon tasks which also engage perceptual processing (Guerreiro & Van Gerven, 2017; Lin et al., 2011a, 2013). Our findings and the findings observed on the Stroop/Simon tasks, which are visual tasks

indicate that inhibitory control changes in ARHL are modality-independent since all participants had normal/corrected vision.

Like the behavioral findings, electrophysiological findings on ERP and ERSP markers tied to Go/NoGo tasks revealed differences between ARHL and NH groups. Group differences in ERPs were observed in the early time periods on N2 ERP. An interaction between group and trial was observed on N2 latency between 150-300 ms on the Single-Car task. This interaction was driven by longer N2 latency on the NoGo relative to Go trials in the ARHL group; however, the NH controls had comparable latencies for both trial types. This finding suggests that older adults with ARHL have prolonged neural processing which may be indicative of greater neural effort in processing the infrequent NoGo relative to the frequent Go trials, whereas those with NH did not exhibit these patterns. Yet again these findings were specific to the Single-Car task, which heavily depends on perceptual processing of two line-drawn exemplars of a car and a dog to make basic categorization decisions. These findings are somewhat consistent with Oates et al. (2013) who also found longer N2 latency on infrequent stimuli on a perceptual oddball paradigm. However, one must note that despite longer N2 latency on the NoGo relative to Go trials, the mild ARHL group had lower accuracy of response on these NoGo trials compared to Go trials on the Single-Car task. Perhaps prolonged neural processing is not sufficient to improve accuracy of response; however, further corroboration of these findings is needed.

Differences across groups and trials were also observed in P3 amplitude between 250-600 ms and high-frequency alpha desynchronization between 300-650 ms on the Object-Animal task. In particular, the NH group had higher P3 amplitude and greater ERD in the high-frequency alpha band on NoGo relative to Go trials. In contrast, the ARHL group showed comparable P3 amplitude and alpha ERD for both NoGo and Go trials. It appears that while NH controls

engaged greater neural resources/effort to process the infrequent NoGo trials relative to the frequent Go trials, these neural differentiations were not noted in the ARHL group. These findings suggest that in individuals with mild ARHL, neural processing pattern on the more complex Object Animal task diverges from NH controls beginning 300 ms post-onset. However, the groups did not differ on behavioral performance on the Object-Animal task, therefore, changes in neural processing observed in the ARHL group appears to be below the threshold to cause any significant behavioral impact. While higher P3 amplitude for NoGo versus Go trials in the NH group was observed on the Object-Animal task, findings of greater ERD in high-frequency alpha for NoGo (relative to Go) trials were noted in both tasks with larger effect size observed on the Object-Animal task. Our ERP findings are consistent with Bertolli et al. (2005) who found higher P3 amplitude in those with NH but not in individuals with ARHL on an oddball paradigm. Given that no other studies have examined ERSPs related to inhibitory control using Go/NoGo tasks, our ERD findings need validation.

Besides examining differences between ARHL and NH groups on inhibitory control, we also investigated associations between central hearing ability and inhibitory control. Only in the ARHL group, a positive association was observed between binaural QuickSIN score and P3 amplitude on NoGo trials on the Object-Animal task. These findings suggest those with poorer SiN recognition within the ARHL group, indicating worse central hearing, engaged more neural resources/effort to process the infrequent NoGo trials. Similar to Go/NoGo tasks, the QuickSIN task involves participants to respond to certain stimuli (repeat back sentences) and suppress responses to others (background multi-talker babble noise). Yet again, correlations were observed in the more complex Object-Animal task, which might be because both QuickSIN and Object-Animal tasks both involved more detailed semantic processing of information. Successful

performance on the QuickSIN task requires recognition of multiple semantically rich sentences in presence of background noise (Killion et al., 2004), and the Object-Animal task requires participants to accurately categorize multiple exemplars into objects and animals (Maguire et al., 2009). The association between binaural QuickSIN score and P3 amplitude was observed even when PTA was factored out, suggesting that the relation between central hearing and inhibitory control goes beyond peripheral hearing deficits as noted by others (Janse, 2012; Shende et al., 2021).

Despite promising findings, this study has some limitations. Our study sample was small, due to recruitment challenges following the COVID-19 pandemic. Examining inhibitory control in ARHL with larger sample size is critical for corroboration and generalization of the current findings. Additionally, a larger sample size would allow utilization of data reduction techniques, such as principal component analysis in identification of electrodes of interest through more data-driven approaches, as opposed to the hypothesis-driven approach used for ERP and ERSP analyses in the current study. Emerging evidence suggests that higher-frequency bands such as beta and gamma are sensitive to hearing loss (Sedley & Cunningham, 2013) and are also related to SiN recognition (Drijvers et al., 2018; Strauß et al., 2014). Our ERSP analyses focused only on low-frequency theta and alpha bands. Future studies examining inhibitory control in ARHL could potentially examine changes in the high-frequency oscillations using techniques other than Fast-Fourier transform (used in current study) such as Morlet wavelet analyses, and whether those are related to SiN recognition. Finally, our findings on alterations in inhibitory control were observed on visual Go/NoGo tasks indicating modality-general changes. However, to understand if these neurophysiological alterations are truly modality-independent, future studies should examine inhibitory control using auditory and visual tasks concurrently.

To conclude, the current study had two goals: (1) investigating alterations in inhibitory control in individuals with unaided mild ARHL relative to NH controls linked to two Go/NoGo tasks (Single-Car/Object Animal) using EEG derived metrics, and (2) examining the association between central hearing and inhibitory control. Different neural processing patterns were observed across Go and NoGo trials in the ARHL and NH groups in both early and later time windows. The mild ARHL group showed N2 latency differences in processing the NoGo versus Go trials on the Single-Car task in early time window. Whereas, the NH group showed differential processing for NoGo versus Go trials on the Object-Animal task in P3 amplitude and high-frequency alpha desynchronization in the later time windows. We also found that individuals with ARHL that had more challenges in SiN recognition exerted more neural resources/effort to complete the Object-Animal task. This was observed as a correlation within the ARHL group, with poor SiN recognition associated with higher P3 amplitude on NoGo trials on the Object-Animal task. Together, our study findings provide new insight into cognitive alterations linked to inhibitory control in individuals with mild ARHL. Given that we used age-matched NH controls as a comparison group, our results suggest that alterations observed in our mild ARHL group is beyond what is expected with normal aging based on the Inhibitory Deficit hypothesis (Hasher & Zacks, 1988).

Since individuals with mild ARHL often do not seek amplification or are inconsistent users of amplification, the extent to which these alterations in inhibitory control will progress with time and increase the risk of dementia needs further examination. Furthermore, the neural alterations were observed in a visual task, which is an unimpaired modality in our study group, suggesting that alterations in inhibitory control may be modality-independent. Our Go/NoGo tasks consisted of pictures that can evoke a language label, and as such performing these tasks

possibly elicited language processing, which requires significant modality-general resources (Martens et al., 2018). It is plausible that, as suggested by the information-degradation and sensory-deprivation hypotheses, our mild ARHL participants routinely employ their modality-independent cognitive resources to support auditory processing at the detriment of other cognitive functions (CHABA, 1988; Schneider & Pichora-Fuller, 2000). Additionally, as proposed by the common-cause hypothesis (Baltes & Lindenberger, 1987; CHABA, 1988), it could be that the common factor of modality-general, aging-related neurodegenerative changes could lead to both ARHL and cognitive control alterations. Perhaps cognitive control deficits in those with unaided ARHL can be alleviated or rather mitigated by provision of (and adherence to) amplification use. Additionally, cognitive strategies could be used in conjunction with hearing aids (or other amplification devices) to prevent cognitive alterations in individuals with ARHL and reduce the risk for cognitive impairment/dementia in this population.

4.5. Tables and Figures

Table 4.1.

Demographic and Participant Characterization Data Across Groups

	ARHL	NH	<i>p</i>
Total N	17	25	--
Age (years)	67.18 (7.26)	66.04 (7.05)	.615
Education (years)	17.82 (3.48)	17.20 (2.30)	.489
Sex	13F/4M	17F/8M	.406
MoCA	27.88 (1.45)	28.08 (1.18)	.631
GDS	0.53 (0.87)	0.48 (0.71)	.842

Each cell represents group mean (standard deviation), except for sex. *p*-values were derived from *F*-statistics of contrasts of experimental factor means for all variables, except sex which was derived from Pearson Chi-square with Yates continuity correction. MoCA: Montreal Cognitive Assessment Scale (Nasreddine et al., 2005); GDS: Geriatric Depression Scale (Almeida & Almedia, 1999). ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Table 4.2.

Audiological Data Across Groups

	ARHL	NH	<i>p</i>
Better ear PTA (dB HL)	32.86 (6.90)	15.90 (5.94)	<.001**
Binaural QuickSIN score	3.00 (2.46)	1.38 (1.37)	.009**
Speech SRT (dB HL)	30.00 (10.00)	18.40 (5.53)	<.001**
Left SRT (dB HL)	31.76 (7.26)	18.00 (5.59)	<.001**
Right WRS (%)	94.82 (8.69)	99.04 (0.47)	.026*
Left WRS (%)	95.29 (6.51)	98.72 (4.11)	.043*

Cells represent means of raw test scores (standard deviation). ARHL = Age-Related Hearing Loss; NH = Normal Hearing; PTA (dB HL) = Pure-Tone Average (decibels hearing level); SRT (dB HL) = Speech Reception Threshold (decibels hearing level); WRS (dB HL) = Word Recognition Score (decibels hearing level); QuickSIN = Quick Speech-in-Noise (Killion et al., 2005).

Values in bold represent significant effects.

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

Table 4.3.*Accuracy and Reaction Times Group Means on the Go/NoGo Task*

Measures by Task	ARHL	NH
<i>Single-Car Task</i>		
Go RT (ms)	343.65 (39.94)	337.35 (38.28)
Go accuracy (%)	0.98 (.02)	0.93 (.10)
NoGo accuracy (%)	0.88 (.05)	0.92 (.06)
<i>Object-Animal Task</i>		
Go RT (ms)	428.50 (43.05)	424.98 (47.64)
Go accuracy (%)	0.95 (.06)	0.93 (.09)
NoGo accuracy (%)	0.87 (.10)	0.92 (.07)

Each cell represents group mean (standard deviation). RT: Reaction time.
 ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Table 4.4.*Accuracy and Reaction Times Data: Statistical Results*

Effects	Go Reaction Time (ms)	Accuracy (%)
<i>Single-Car Task</i>		
Group	$F(1,38) = 0.26, p = .610, \eta^2 = .007$	$F(1,38) = 0.05, p = .819, \eta^2 = .001$
Trial type	N.A.	$F(1,38) = 9.29, p = .004^{**}, \eta^2 = .196$
Group x trial type	N.A.	$F(1,38) = 5.97, p = .019^*, \eta^2 = .136$
<i>Object-Animal Task</i>		
Group	$F(1,40) = 0.05, p = .809, \eta^2 = .001$	$F(1,40) = 0.93, p = .341, \eta^2 = .023$
Trial type	N.A.	$F(1,40) = 6.76, p = .013^*, \eta^2 = .145$
Group x trial type	N.A.	$F(1,40) = 3.45, p = .071, \eta^2 = .079$

Group: ARHL/NH; Trial: Go/NoGo. ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Values in bold represent significant effects.

* $p < .05$, ** $p < .01$.

Table 4.5.*N2 and P3 Latency and Amplitude Group Means*

		Single-Car Task				Object-Animal Task			
		Latency (ms)		Mean Amplitude (μV)		Latency (ms)		Mean Amplitude (μV)	
N2		ARHL	NH	ARHL	NH	ARHL	NH	ARHL	NH
	Go	218.13 (23.73)	225.02 (26.53)	-0.20 (0.78)	-0.32 (0.66)	235.44 (22.41)	228.73 (18.01)	-0.23 (0.74)	-0.44 (1.04)
	NoGo	241.29 (32.77)	224.38 (23.76)	-0.03 (0.87)	-0.39 (0.81)	244.32 (31.05)	234.49 (22.50)	-0.31 (0.73)	-0.54 (0.96)
P3	Go	366.10 (41.15)	371.48 (61.00)	0.36 (0.35)	0.40 (0.46)	430.26 (46.73)	428.35 (56.30)	0.36 (0.34)	0.39 (0.48)
	NoGo	381.38 (31.79)	381.66 (46.28)	0.37 (0.30)	0.51 (0.60)	411.54 (54.94)	419.55 (53.89)	0.36 (0.39)	0.55 (0.56)

Each cell represents group mean (standard deviation). ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Table 4.6.*N2 and P3 Latencies and Amplitudes: Statistical Results*

		Single-Car Task						Object-Animal Task					
		Latency (ms)			Mean Amplitude (μV)			Latency (ms)			Mean Amplitude (μV)		
		<i>F</i> (1,38)	<i>p</i>	η ²	<i>F</i> (1,38)	<i>p</i>	η ²	<i>F</i> (1,40)	<i>p</i>	η ²	<i>F</i> (1,40)	<i>p</i>	η ²
N2	Group	0.41	.524	.011	0.92	.342	.024	1.55	.220	.037	0.62	.432	.015
	Trial type	9.52	.004**	.200	0.45	.506	.012	5.66	.022*	.124	3.39	.073	.078
	Group x trial type	10.63	.002**	.219	2.55	.119	.063	0.25	.614	.006	0.04	.836	.001
P3	Group	0.04	.828	.001	0.41	.523	.011	0.04	.841	.001	0.58	.449	.014
	Trial type	1.94	.171	.049	1.53	.223	.039	3.41	.072	.079	4.64	.037*	.104
	Group x trial type	0.07	.781	.002	1.08	.303	.028	0.44	.509	.001	4.88	.033*	.109

Group: ARHL/NH; Trial: Go/NoGo. ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Values in bold represent significant effects.

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

Table 4.7.*Event-Related Synchronization Group Means for Theta Band*

	Single-Car Task				Object-Animal Task			
	150-300 ms		300-650 ms		150-300 ms		300-650 ms	
	ARHL	NH	ARHL	NH	ARHL	NH	ARHL	NH
<u>Frontal</u>								
Go	2.85 (1.47)	3.08 (1.93)	2.05 (1.16)	2.24 (1.41)	3.02 (1.77)	3.60 (1.96)	1.97 (1.29)	2.74 (1.67)
NoGo	3.25 (1.77)	3.82 (2.04)	1.73 (0.86)	2.11 (0.97)	3.13 (2.09)	3.84 (2.01)	1.67 (0.92)	2.19 (1.14)
<u>Fronto-central</u>								
Go	2.68 (1.29)	2.81 (1.67)	1.81 (0.83)	1.95 (1.13)	2.62 (2.17)	3.13 (1.95)	1.88 (1.14)	2.25 (1.49)
NoGo	3.35 (1.32)	3.90 (2.18)	2.04 (0.86)	2.10 (0.96)	3.12 (1.68)	3.62 (1.86)	1.81 (0.93)	2.21 (1.09)
<u>Central</u>								
Go	1.82 (1.40)	1.69 (1.39)	1.32 (0.67)	1.33 (0.99)	1.67 (1.24)	1.76 (1.27)	1.44 (0.70)	1.63 (1.04)
NoGo	2.61 (1.33)	2.96 (1.79)	1.82 (0.80)	2.00 (1.10)	2.29 (1.46)	2.20 (1.28)	1.70 (0.60)	2.15 (1.04)
<u>Centro-parietal</u>								
Go	1.48 (1.00)	1.77 (1.25)	1.45 (1.1)	1.68 (1.36)	1.51 (1.36)	1.65 (1.02)	1.56 (1.18)	1.31 (0.81)
NoGo	1.88 (1.13)	2.77 (2.56)	1.26 (0.54)	1.78 (1.05)	1.79 (1.44)	2.06 (1.05)	1.81 (1.31)	1.91 (1.22)
<u>Parietal</u>								
Go	2.36 (1.33)	2.52 (1.87)	1.79 (1.07)	1.32 (0.70)	2.17 (1.75)	3.09 (2.11)	1.60 (1.14)	2.14 (1.11)
NoGo	2.64 (1.62)	3.36 (2.00)	1.32 (0.70)	1.66 (0.90)	2.70 (1.92)	3.67 (2.28)	1.64 (0.95)	2.06 (1.05)

Each cell represents group mean (standard deviation) in dB. ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Table 4.8.*Event-Related Desynchronization Group Means for Low-Frequency Alpha Band*

	Single-Car Task				Object-Animal Task			
	150-300 ms		300-650 ms		150-300 ms		300-650 ms	
	ARHL	NH	ARHL	NH	ARHL	NH	ARHL	NH
<u>Frontal</u>								
Go	-0.81 (0.85)	-1.08 (1.16)	-0.71 (0.76)	-1.16 (1.24)	-1.17 (1.02)	-0.96 (1.12)	-1.42 (1.34)	-1.23 (1.41)
NoGo	-0.88 (0.64)	-0.89 (1.05)	-1.44 (0.92)	-1.85 (1.14)	-1.27 (1.26)	-0.89 (1.12)	-2.27 (1.97)	-2.02 (1.62)
<u>Fronto-central</u>								
Go	-0.89 (0.89)	-1.11 (1.15)	-1.06 (0.88)	-1.30 (1.37)	-1.20 (0.93)	-1.08 (1.24)	-1.52 (1.30)	-1.48 (1.55)
NoGo	-0.91 (0.82)	-1.00 (1.07)	-1.58 (1.04)	-2.04 (1.29)	-1.28 (1.13)	-0.95 (0.99)	-2.16 (1.84)	-2.24 (1.77)
<u>Central</u>								
Go	-1.19 (1.13)	-1.66 (1.63)	-1.22 (0.87)	-1.90 (1.81)	-1.47 (1.34)	-1.56 (1.85)	-1.69 (1.10)	-2.36 (2.42)
NoGo	-1.35 (1.42)	-1.44 (1.64)	-1.95 (1.13)	-2.56 (2.04)	-1.36 (1.33)	-1.63 (1.81)	-2.12 (1.42)	-3.06 (2.54)
<u>Centro-parietal</u>								
Go	-1.51 (1.40)	-1.71 (1.74)	-1.32 (1.36)	-1.84 (1.91)	-1.73 (1.84)	-1.67 (1.98)	-1.83 (1.67)	-2.13 (2.22)
NoGo	-1.54 (1.69)	-1.58 (1.87)	-2.24 (1.31)	-2.54 (2.06)	-1.64 (1.79)	-1.58 (1.85)	-2.39 (1.90)	-2.84 (2.35)
<u>Parietal</u>								
Go	-1.26 (1.15)	-1.43 (1.62)	-1.22 (1.15)	-1.45 (1.68)	-1.57 (1.51)	-1.38 (1.71)	-1.74 (1.63)	-1.64 (1.81)
NoGo	-1.36 (1.42)	-1.41 (1.77)	-2.15 (1.23)	-2.40 (1.91)	-1.46 (1.54)	-1.25 (1.89)	-2.40 (2.03)	-2.48 (2.07)

Each cell represents group mean (standard deviation) in dB. ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Table 4.9.*Event-Related Desynchronization Group Means for High-Frequency Alpha Band*

	Single-Car Task				Object-Animal Task			
	150-300 ms		300-650 ms		150-300 ms		300-650 ms	
	ARHL	NH	ARHL	NH	ARHL	NH	ARHL	NH
<i><u>Frontal</u></i>								
Go	-1.46 (0.98)	-1.58 (1.29)	-1.19 (0.86)	-1.66 (1.29)	-1.81 (0.72)	-1.54 (1.09)	-1.99 (0.87)	-1.89 (1.56)
NoGo	-1.24 (0.76)	-1.42 (1.21)	-1.42 (0.78)	-2.13 (1.34)	-1.58 (0.88)	-1.45 (1.02)	-2.32 (1.32)	-2.54 (1.52)
<i><u>Fronto-central</u></i>								
Go	-1.54 (0.85)	-1.56 (1.19)	-1.59 (0.83)	-1.62 (1.27)	-1.81 (0.68)	-1.61 (1.09)	-1.99 (0.89)	-1.99 (1.59)
NoGo	-1.47 (0.85)	-1.43 (1.17)	-1.69 (0.86)	-2.26 (1.26)	-1.48 (0.78)	-1.36 (0.93)	-2.29 (1.28)	-2.55 (1.65)
<i><u>Central</u></i>								
Go	-1.80 (0.75)	-1.86 (1.51)	-1.65 (0.84)	-1.98 (1.68)	-1.89 (0.82)	-1.86 (1.58)	-2.02 (0.91)	-2.51 (2.31)
NoGo	-1.73 (0.92)	-1.81 (1.59)	-1.96 (0.99)	-2.66 (1.91)	-1.56 (0.78)	-1.80 (1.48)	-2.08 (1.10)	-3.15 (2.43)
<i><u>Centro-parietal</u></i>								
Go	-1.85 (1.01)	-2.07 (1.64)	-1.52 (1.19)	-1.96 (1.81)	-1.84 (0.89)	-2.09 (1.78)	-1.93 (1.21)	-2.44 (2.12)
NoGo	-2.02 (0.87)	-2.18 (1.90)	-2.24 (1.90)	-2.77 (1.94)	-1.79 (1.00)	-1.92 (1.75)	-2.24 (1.33)	-3.06 (2.25)
<i><u>Parietal</u></i>								
Go	-1.71 (1.00)	-2.04 (1.59)	-1.32 (0.95)	-1.79 (1.60)	-1.86 (0.88)	-1.94 (1.67)	-1.90 (1.11)	-2.27 (2.00)
NoGo	-1.80 (0.87)	-2.03 (1.85)	-2.02 (1.03)	-2.65 (1.92)	-1.63 (0.94)	-1.76 (1.81)	-2.36 (1.32)	-2.89 (2.16)

Each cell represents group mean (standard deviation) in dB. ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Table 4.10.

Event-Related Synchronization in Theta Band: Statistical Results

	Single-Car Task						Object-Animal Task					
	150-300 ms			300-650 ms			150-300 ms			300-650 ms		
	<i>F</i> (1,38)	<i>p</i>	η^2	<i>F</i> (1,38)	<i>p</i>	η^2	<i>F</i> (1,40)	<i>p</i>	η^2	<i>F</i> (1,40)	<i>p</i>	η^2
<u><i>Frontal</i></u>												
Group	0.46	.501	.012	0.87	.354	.023	1.16	.287	.028	2.92	.095	.068
Trial	10.18	.003**	.211	0.93	.330	.025	1.27	.267	.031	5.97	.019**	.130
Group x Trial	0.88	.354	.023	0.17	.681	.005	0.16	.690	.004	0.46	.500	.011
<u><i>Fronto-central</i></u>												
Group	0.40	.529	.011	0.15	.697	.004	0.82	.370	.020	1.21	.277	.029
Trial	22.11	<.001**	.368	1.13	.294	.029	21.34	<.001**	.348	0.13	.721	.003
Group x Trial	1.26	.268	.032	0.04	.832	.001	0.00	.991	.000	0.01	.920	.000
<u><i>Central</i></u>												
Group	0.05	.811	.002	0.15	.697	.004	0.02	.874	.001	1.54	.222	.038
Trial	27.18	<.001**	.417	10.46	.003**	.216	23.32	<.001**	.374	7.43	.010*	.160
Group x Trial	1.44	.237	.037	0.22	.639	.006	1.61	.211	.040	0.87	.356	.022
<u><i>Centro-parietal</i></u>												
Group	2.78	.104	.068	1.57	.217	.040	0.31	.577	.008	1.55	.219	.037
Trial	18.21	<.001**	.32	0.04	.829	.001	9.73	.003**	.196	0.23	.633	.006
Group x Trial	3.29	.077	.080	0.53	.470	.014	0.37	.547	.009	1.44	.236	.035
<u><i>Parietal</i></u>												
Group	0.62	.435	.016	0.66	.420	.017	2.22	.144	.053	2.47	.124	.058
Trial	12.19	.001**	.238	3.83	.057	.090	16.56	<.001**	.293	0.35	.852	.001
Group x Trial	3.11	.086	.074	0.33	.567	.008	0.25	.876	.001	0.18	.670	.005

Group: ARHL/NH; Trial: Go/NoGo. ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Values in bold represent significant effects.

* $p < .05$, ** $p < .01$.

Table 4.11.

Event-Related Desynchronization in Low-Frequency Alpha Band: Statistical Results

	Single-Car Task						Object-Animal Task					
	150-300 ms			300-650 ms			150-300 ms			300-650 ms		
	<i>F</i> (1,38)	<i>p</i>	η^2	<i>F</i> (1,38)	<i>p</i>	η^2	<i>F</i> (1,40)	<i>p</i>	η^2	<i>F</i> (1,40)	<i>p</i>	η^2
<i>Frontal</i>												
Group	0.22	.639	.006	1.62	.210	.041	0.72	.401	.018	0.20	.657	.005
Trial	0.17	.676	.005	40.92	<.001**	.513	0.03	.845	.001	55.70	<.001**	.582
Group x Trial	1.08	.303	.028	0.03	.845	.001	1.03	.316	.025	0.06	.795	.002
<i>Fronto-central</i>												
Group	0.21	.303	.028	0.83	.367	.021	0.44	.509	.011	0.01	.969	.000
Trial	0.21	.644	.006	40.94	<.001**	.519	0.12	.730	.003	50.17	<.001**	.556
Group x Trial	0.46	.643	.006	1.26	.268	.032	1.78	.189	.043	0.39	.533	.010
<i>Central</i>												
Group	0.34	.559	.009	1.47	.233	.037	0.12	.728	.003	1.53	.223	.037
Trial	0.07	.788	.002	51.12	<.001**	.574	0.04	.838	.001	42.90	.001**	.518
Group x Trial	2.57	.117	.063	0.13	.715	.004	0.63	.430	.016	2.54	.119	.060
<i>Centro-parietal</i>												
Group	0.04	.837	.001	0.51	.478	.013	0.01	.918	.000	0.32	.572	.008
Trial	0.13	.715	.004	53.74	<.001**	.586	0.93	.340	.023	56.21	<.001**	.584
Group x Trial	0.36	.551	.009	0.91	.345	.024	0.01	.945	.000	0.73	.396	.001
<i>Parietal</i>												
Group	0.05	.822	.001	0.21	.643	.006	0.14	.702	.004	0.00	.988	.000
Trial	0.09	.757	.003	61.31	.001**	.617	1.37	.248	.033	50.00	<.001**	.556
Group x Trial	0.23	.631	.006	0.01	.953	.000	0.01	.912	.000	0.72	.399	.018

Group: ARHL/NH; Trial: Go/NoGo. ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Values in bold represent significant effects.

* $p < .05$, ** $p < .01$.

Table 4.12.

Event-Related Desynchronization in High-Frequency Alpha Band: Statistical Results

	Single-Car Task						Object-Animal Task					
	150-300 ms			300-650 ms			150-300 ms			300-650 ms		
	<i>F</i> (1,38)	<i>p</i>	η^2	<i>F</i> (1,38)	<i>p</i>	η^2	<i>F</i> (1,40)	<i>p</i>	η^2	<i>F</i> (1,40)	<i>p</i>	η^2
<u><i>Frontal</i></u>												
Group	0.18	.672	.005	2.67	.110	.066	0.48	.491	.012	0.01	.891	.000
Trial	2.12	.153	.053	8.46	<.006**	.182	2.51	.121	.059	16.21	<.001**	.288
Group x Trial	0.04	.829	.001	0.95	.334	.025	0.40	.527	.010	1.67	.204	.040
<u><i>Fronto-central</i></u>												
Group	0.01	.967	.000	0.70	.408	.018	0.37	.545	.009	0.08	.770	.002
Trial	0.77	.386	.020	11.47	.002**	.232	10.62	.002**	.210	15.06	<.001**	.274
Group x Trial	0.05	.809	.002	6.00	.019*	.137	0.22	.642	.005	1.37	.248	.033
<u><i>Central</i></u>												
Group	0.03	.861	.001	1.08	.304	.028	0.07	.786	.002	1.65	.206,	.040
Trial	0.19	.663	.005	18.95	.001**	.333	3.91	.055	.089	14.98	<.001**	.273
Group x Trial	0.00	.923	.000	2.62	.113	.065	2.00	.165	.048	10.68	.002**	.211
<u><i>Centro-parietal</i></u>												
Group	0.15	.701	.004	0.84	.363	.022	0.17	.677	.004	1.32	.256	.032
Trial	1.27	.266	.032	52.21	<.001**	.579	1.18	.283	.029	26.68	<.001**	.400
Group x Trial	0.08	.779	.002	0.17	.678	.005	0.32	.569	.008	2.99	.091	.070
<u><i>Parietal</i></u>												
Group	1.30	.261	.033	0.34	.558	.009	0.05	.811	.001	0.65	.425	.016
Trial	42.98	.001**	.531	0.09	.761	.002	2.95	.093	.069	29.35	<.001**	.423
Group x Trial	0.43	.512	.011	0.14	.710	.004	0.05	.824	.001	0.61	.439	.015

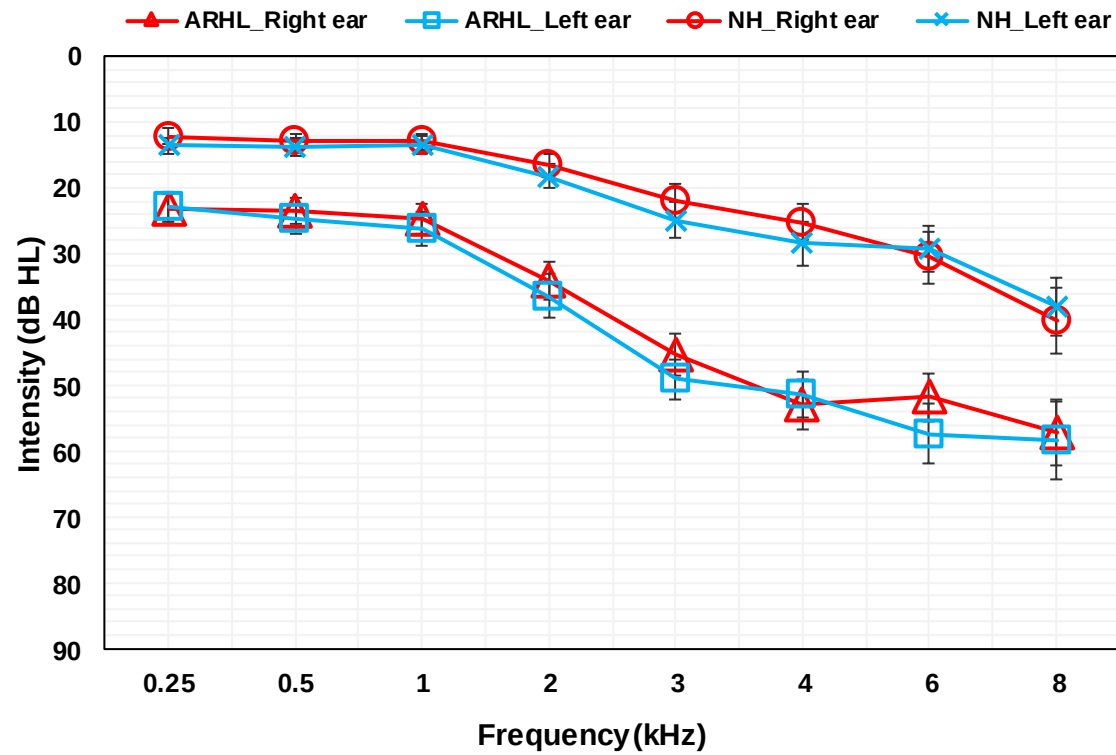
Group: ARHL/NH; Trial: Go/NoGo. ARHL = Age-Related Hearing Loss; NH = Normal Hearing.

Values in bold represent significant effects.

* $p < .05$, ** $p < .01$.

Figure 4.1.

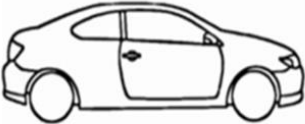
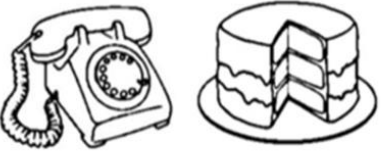
Audiograms for ARHL and NH groups



Note. Average of air conduction hearing thresholds for both ears across frequencies in Age-Related Hearing Loss (ARHL) and Normal Hearing (NH) groups. Error bars represent standard errors.

Figure 4.2.

EEG Task

	Go	NoGo
Single-Car Task		
Object-Animal Task		

Instruction: “You are going to see some dogs/animals and cars/objects. When you see a dog/animal, do not push the button. Press the button for anything that is not a/an dog/animal. Be as quick and as accurate as possible”.

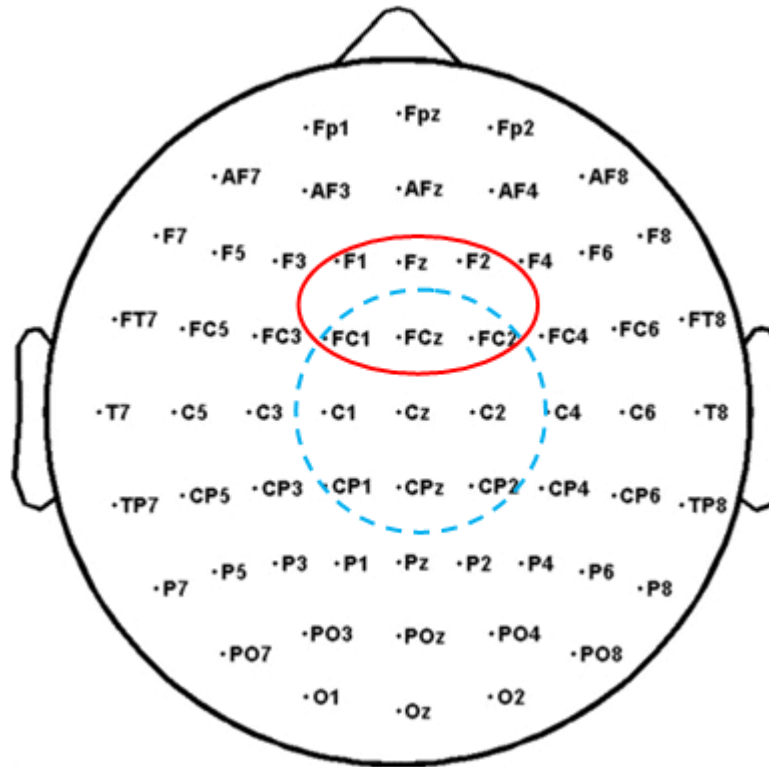
Car/Objects (Go Item): 160 Trials (80%)

Dog/Animals (NoGo Item): 40 Trials (20%)

Note. Single-Car and Object-Animal Go/NoGo task depicting a few exemplars for Go/NoGo trials.

Figure 4.3.

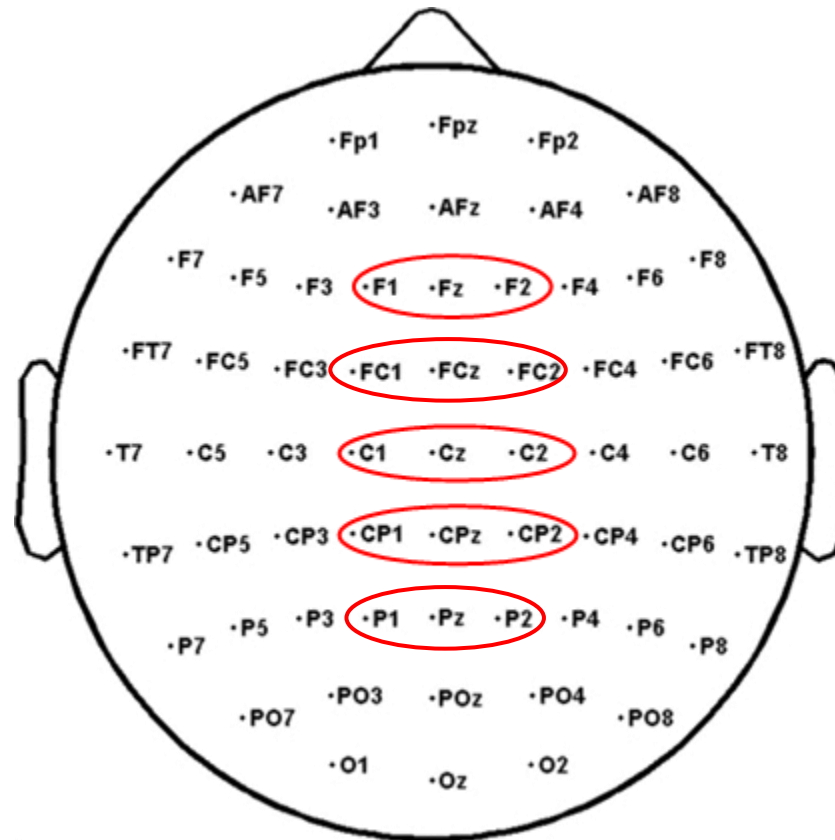
Electrodes Used for Event-Related Potential (ERP) Analysis



Note. Electrodes used for N2 analysis (enclosed by solid red line) and P3 analysis (enclosed by dashed blue lines). Six electrodes were included for N2 analysis over the frontal (F1, Fz, F2) and frontocentral (FC1, FCz, FC2) scalp sites. Nine electrodes included for P3 analysis over the frontocentral (FC1, FCz, FC2), central (C1, Cz, C2), and centroparietal (CP1, CPz, CP2) scalp sites.

Figure 4.4.

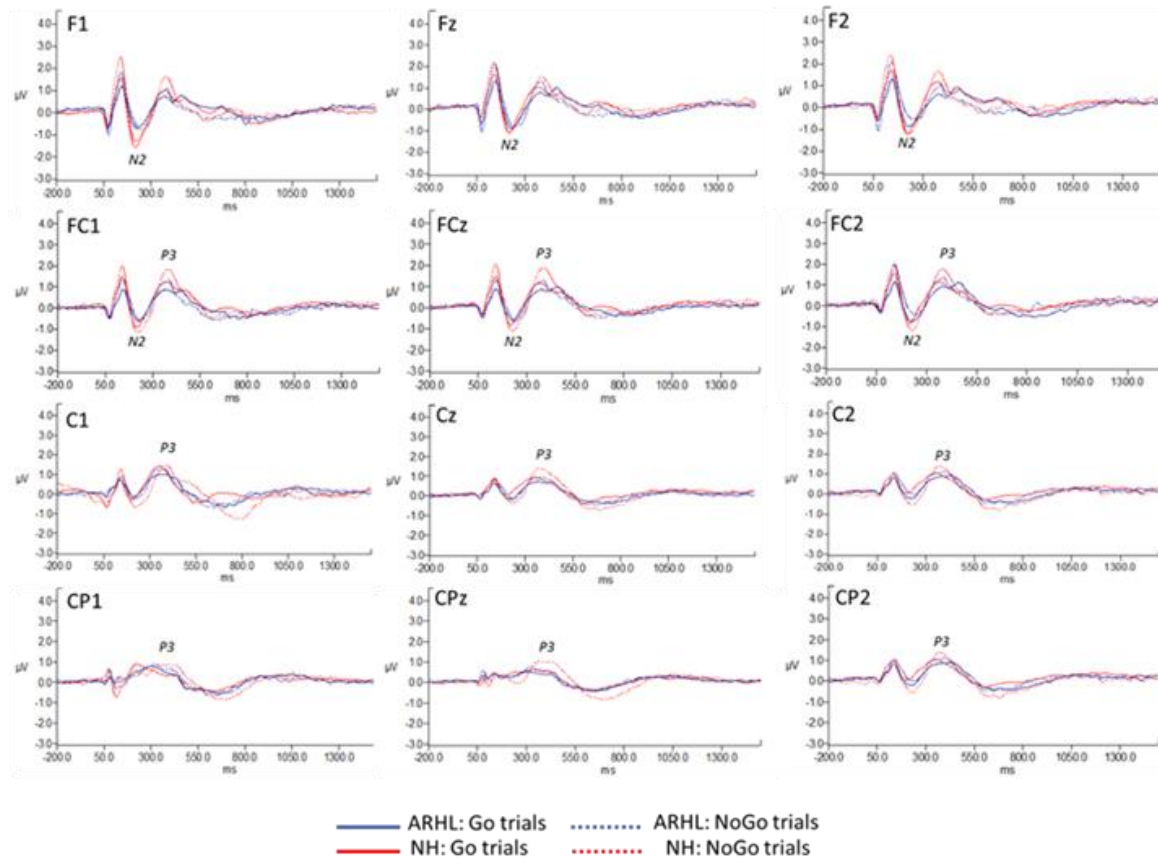
Electrodes Used for Event-Related Spectral Perturbation (ERSP) Analysis



Note. Electrodes used for analyses in theta, low-frequency alpha, and high-frequency alpha bands (enclosed by solid red line). Analyses was done for frontal (F1, Fz, F2), frontocentral (FC1, FCz, FC2), central (C1, Cz, C2), centroparietal (CP1, CPz, CP2) and parietal (P1, Pz, P2) scalp sites.

Figure 4.5.

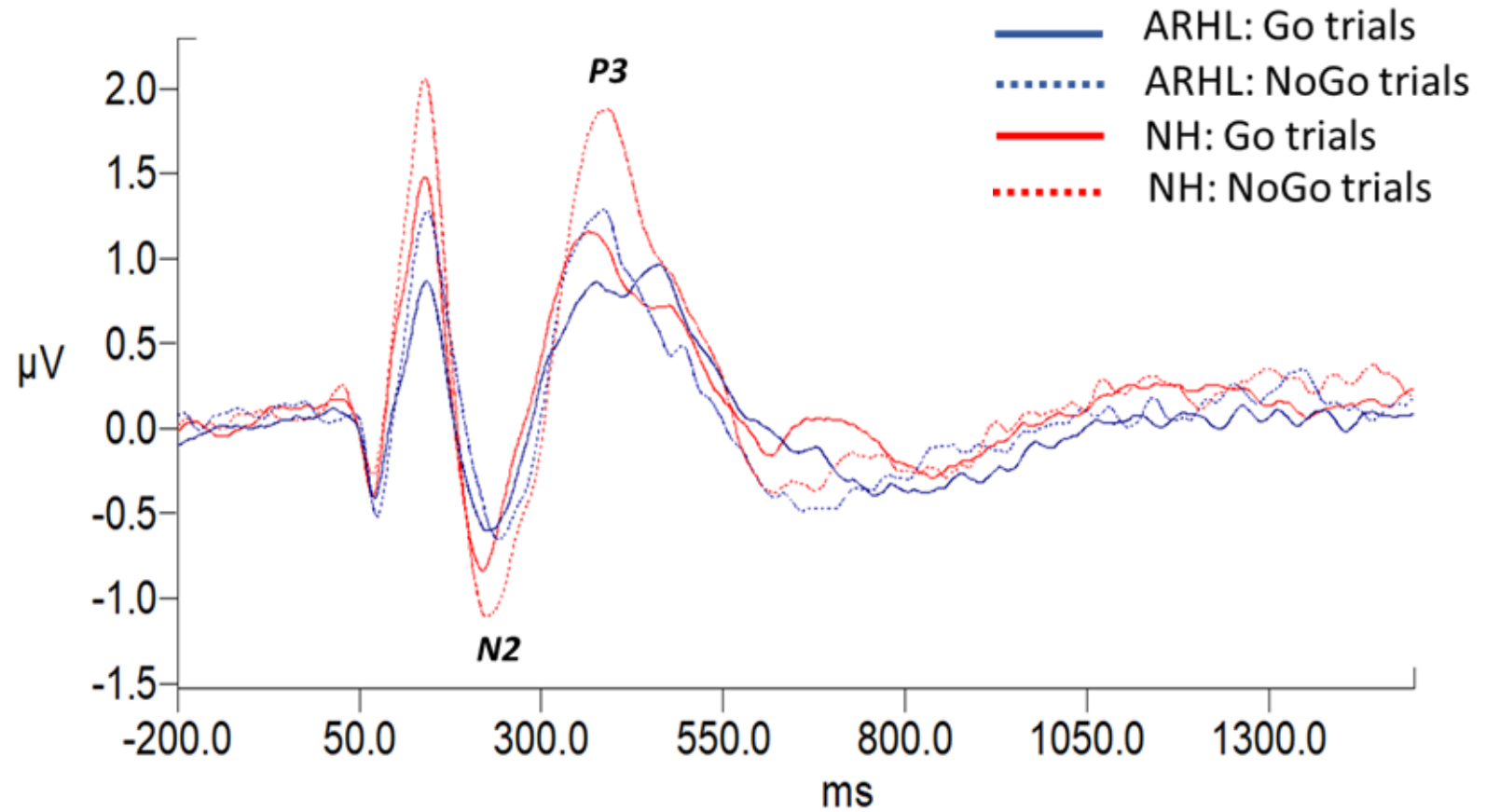
Grand Average Event-Related Potentials (ERPs) with N2 and P3 in the Single-Car task



Note. N2 ERPs examined at average of frontal (F1, Fz, F2) and frontocentral (FC1, FCz, FC2) electrode clusters. P3 ERPs examined average of frontocentral (FC1, FCz, FC2), central (C1, Cz, C2), and centroparietal (CP1, CPz, CP2) electrode clusters. Blue lines indicate Age-Related Hearing Loss (ARHL) group, red lines indicate Normal Hearing (NH) group; solid lines indicate Go trials, dotted lines indicate NoGo trials.

Figure 4.6.

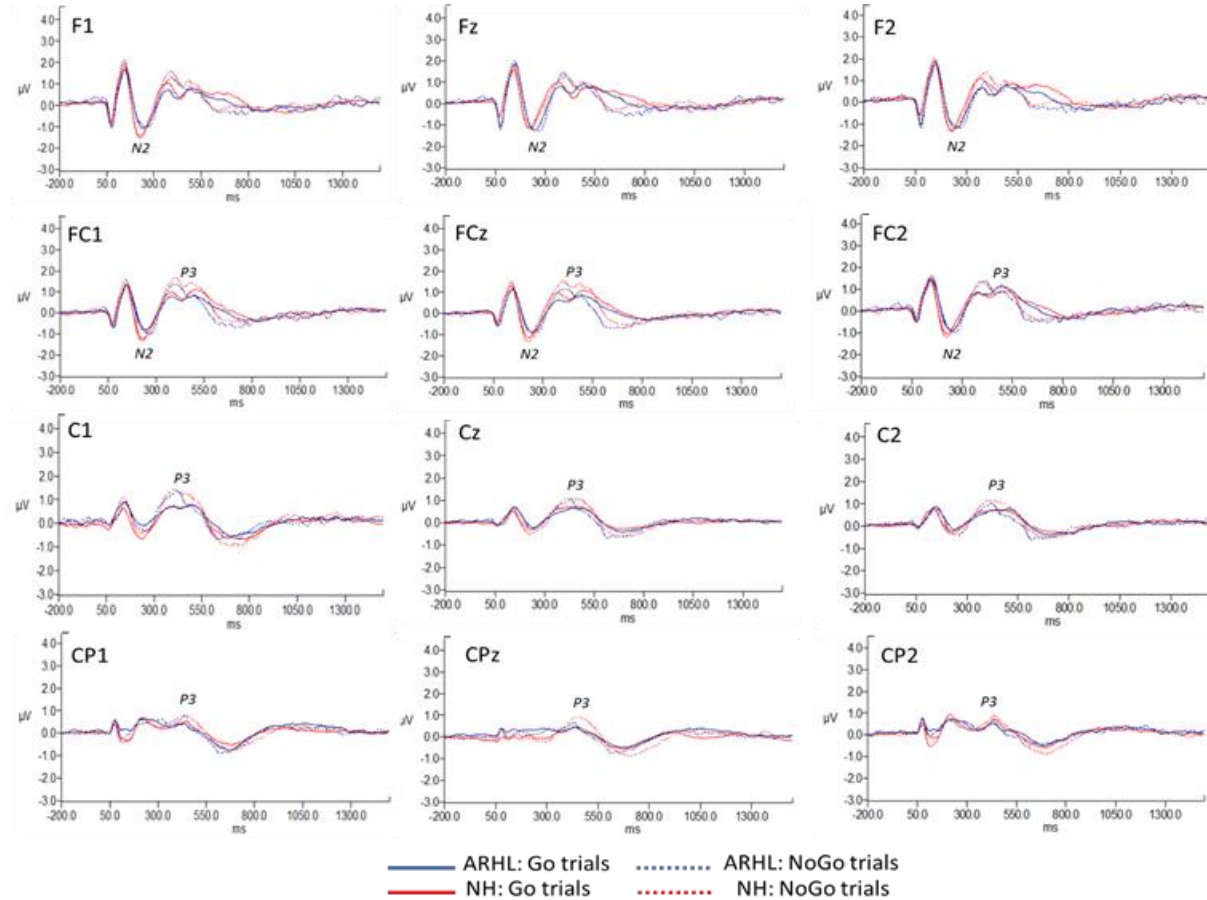
Magnified Grand Average Event-Related Potentials (ERPs) with N2 and P3 in the Single-Car Task at FCz Electrode



Note. Blue lines indicate Age-Related Hearing Loss (ARHL) group, red lines indicate Normal Hearing (NH) group; solid lines indicate Go trials, dotted lines indicate NoGo trials.

Figure 4.7.

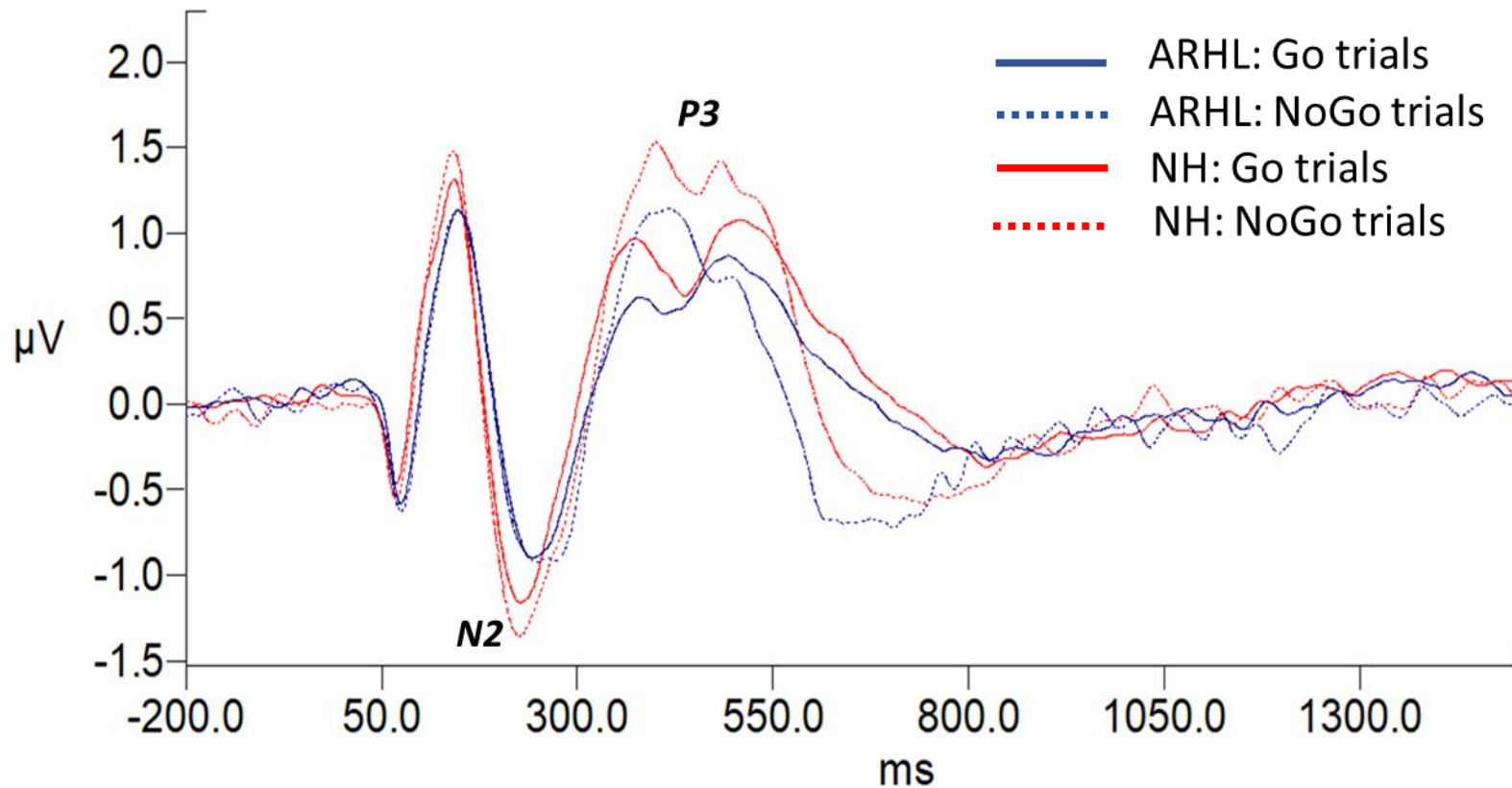
Grand Average Event-Related Potentials (ERPs) with N2 and P3 in the Object-Animal Task.



Note. N2 ERPs examined at average of frontal (F1, Fz, F2) and frontocentral (FC1, FCz, FC2) electrode clusters. P3 ERPs examined average of frontocentral (FC1, FCz, FC2), central (C1, Cz, C2), and centroparietal (CP1, CPz, CP2) electrode clusters. Blue lines indicate Age-Related Hearing Loss (ARHL) group, red lines indicate Normal Hearing (NH) group; solid lines indicate Go trials, dotted lines indicate NoGo trials.

Figure 4.8.

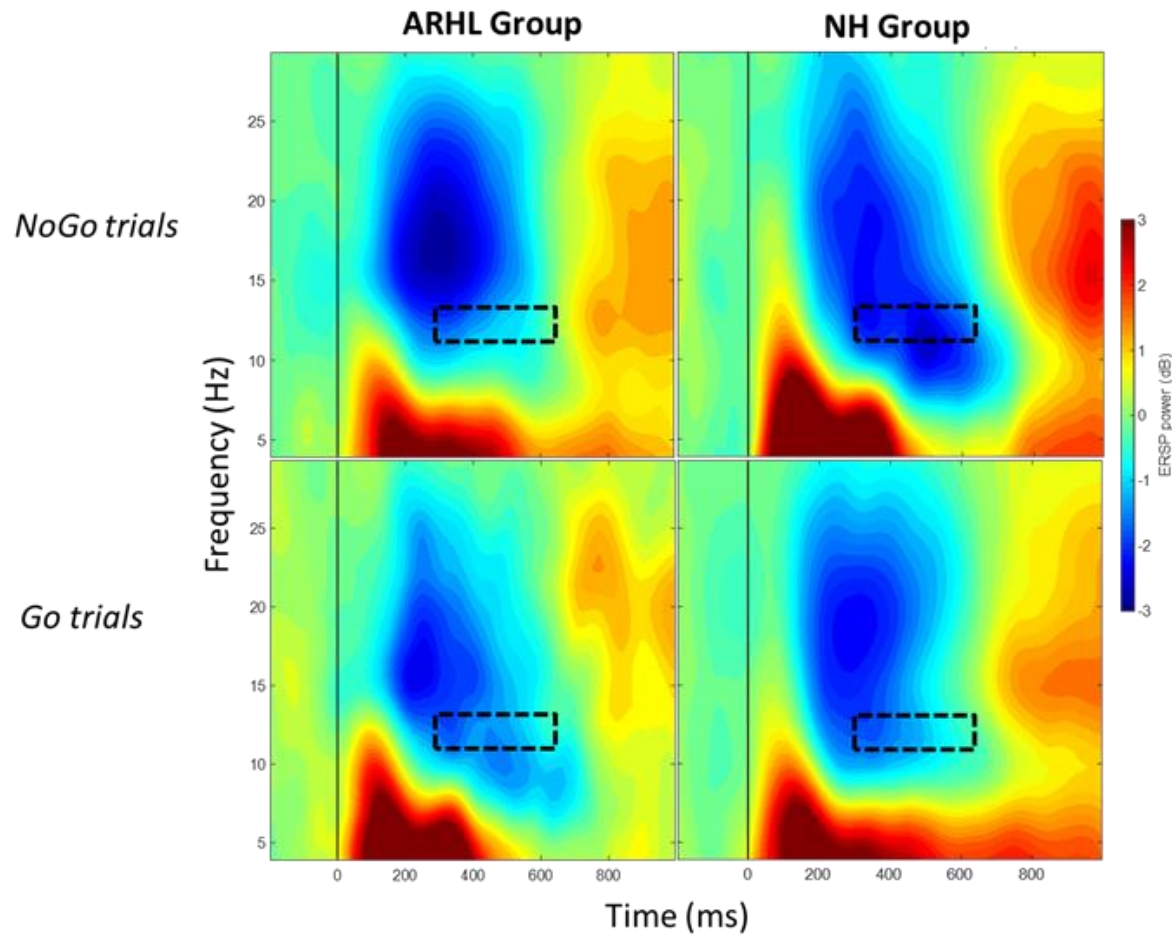
Magnified Grand Average Event-Related Potentials (ERPs) with N2 and P3 in the Object-Animal Task at FCz electrode.



Note. Blue lines indicate Age-Related Hearing Loss (ARHL) group, red lines indicate Normal Hearing (NH) group; solid lines indicate Go trials, dotted lines indicate NoGo trials.

Figure 4.9.

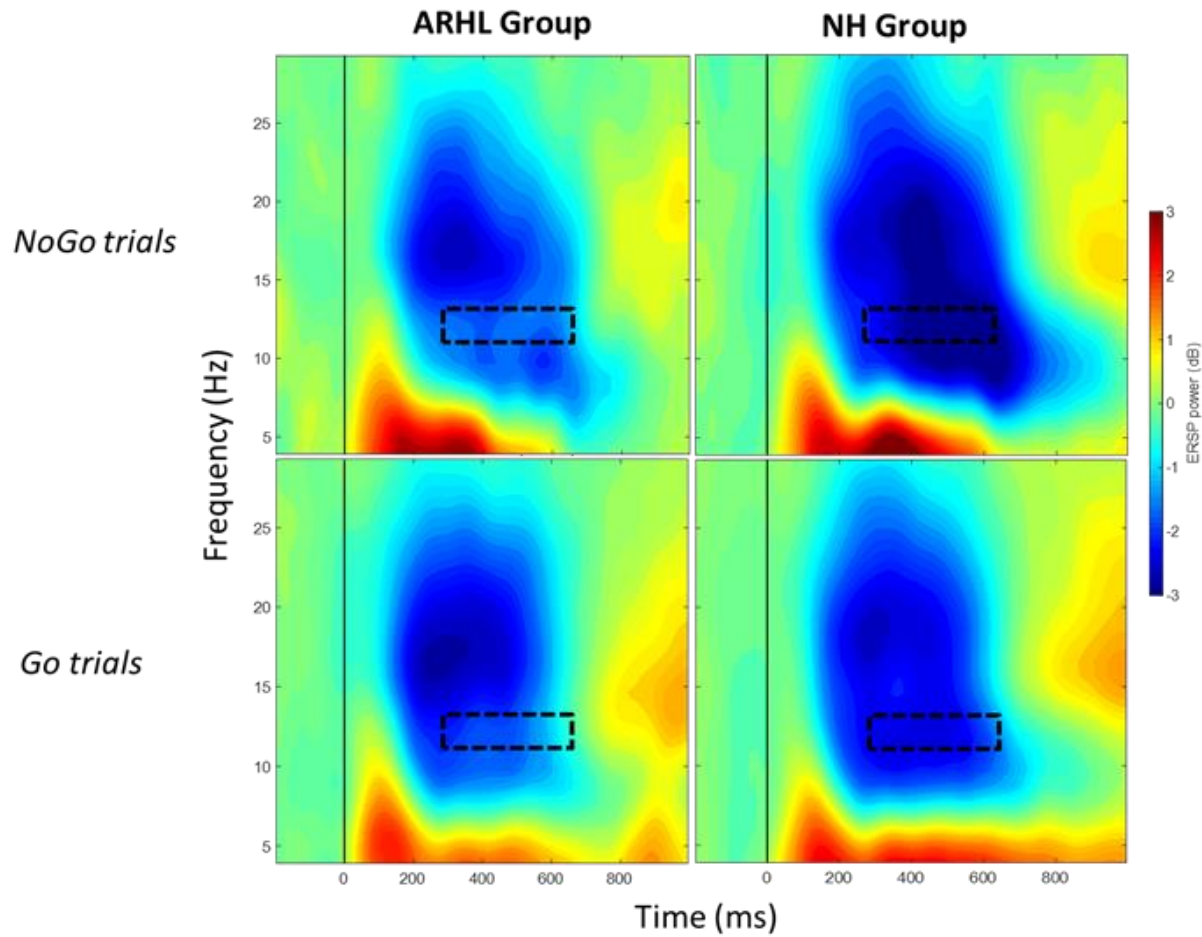
Spectrograms for Group by Trial Interaction Effect in the Frontocentral Electrode Cluster for the Single-Car Task



Note. The spectrograms illustrate differences between trials (Go/NoGo) for the Age-Related Hearing Loss (ARHL) and Normal Hearing (NH) groups. The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate significant effects observed in high-frequency alpha band (11-13 Hz) between 300-650 ms.

Figure 4.10.

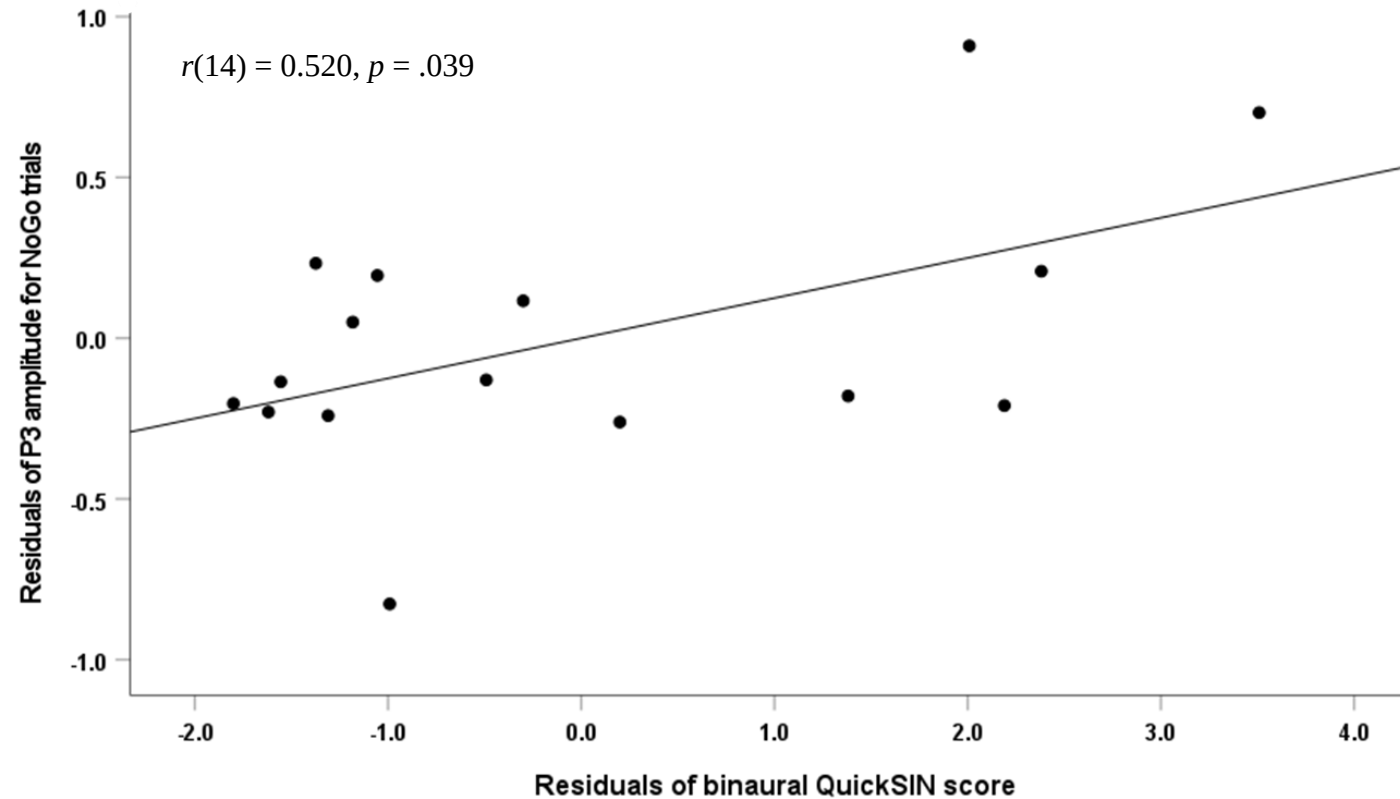
Spectrograms for Group by Trial Interaction Effect in the Central Electrode Cluster for the Object-Animal Task



Note. The spectrograms illustrate differences between trials (Go/NoGo) for the Age-Related Hearing Loss (ARHL) and Normal Hearing (NH) groups. The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate significant effects observed in high-frequency alpha band (11-13 Hz) between 300-650 ms.

Figure 4.11.

Significant Association between Central Hearing and Inhibitory Control within ARHL Group



Note. Partial Pearson correlation plot representing association between binaural QuickSIN score and P3 ERP amplitude for NoGo trials after controlling for peripheral hearing ability. ARHL: Age-Related Hearing Loss (ARHL).

4.6. References

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Chapter 5. Summary and Future Directions

5.1. Summary

This dissertation examined cognitive control changes in older adults with age-related hearing loss (ARHL) in three studies, the findings of each informing the goal of the next. In the first study, the literature on associations between peripheral hearing acuity and common processes of cognitive control, cognitive flexibility, inhibitory control, and working memory updating, in ARHL were reviewed. Additionally, link between speech-in-noise (SiN) recognition, a common issue in ARHL, and the three cognitive control processes were also reviewed (Chapter 2). Consistent evidence was found for associations between hearing ability and cognitive flexibility, working memory updating involving complex tasks in individuals with ARHL; whereas, evidence for association between hearing ability and inhibitory control was mixed. Cognitive flexibility and inhibitory control were less frequently studied relative to working memory and few examined more than one cognitive control processes in older adults with ARHL serving as a motivation for studies two and three. Cognitive flexibility (Chapter 3) and inhibitory control (Chapter 3, 4) in unaided mild ARHL relative to age- and education-matched normal hearing (NH) controls were examined. The link between SiN recognition and cognitive control was also assessed. Two main findings emerged from these two studies: (1) inhibitory control alterations were observed in individuals with unaided mild ARHL at behavioral and neurophysiological levels, and (2) SiN recognition was associated with cognitive flexibility and inhibitory control. See **Figure. 5.1.**, which illustrates a summary of the studies conducted as part of this dissertation.

Behavioral and Neural Alterations in Inhibitory Control

On examination of behavioral changes in cognitive flexibility and inhibitory control (Chapter 3), no changes were found in cognitive flexibility in unaided mild ARHL when compared to age-matched NH controls; however, alterations were observed in inhibitory control (Chapter 3). Furthermore, differences in neurophysiological patterns linked to inhibitory control were also found in individuals with mild ARHL compared to NH controls (Chapter 4). Behaviorally, individuals with mild ARHL had difficulty in inhibiting responses that were goal-irrelevant (indexed by poor accuracy on NoGo trials) compared to Go trials. Neurally, inhibitory control alterations manifested as prolonged N2 latency on NoGo compared to Go trials and lack of differential processing of NoGo and Go trials on P3 amplitude relative to NH controls.

Our findings suggest that even mild ARHL affects inhibitory control. Inhibitory control has been heavily studied in the context of healthy aging (see Campbell et al., 2020 for review). Given that our mild ARHL group involved older adults, as suggested by the Inhibitory Deficit hypothesis (Hasher & Zacks, 1988), reduced effectiveness in inhibitory control would be expected. Since we used a NH control group that was matched for age and education as a comparison, it appears that alterations in mild ARHL go beyond what is expected of typical aging. However, aging-related neurodegenerative changes that affect both hearing and cognition cannot be disregarded. In fact, as suggested by the common-cause hypothesis, (CHABA, 1988; Lindenberger & Baltes, 1994), common factors related to aging, including vascular changes, could lead to both ARHL and inhibitory control alterations. Our findings of inhibitory control changes in individuals with ARHL can also be discussed in the context of the information-degradation (CHABA, 1988; Schneider & Pichora-Fuller, 2000) and sensory-deprivation (CHABA, 1988; Lindenberger & Baltes, 1994; Oster, 1976) hypotheses. Likely, limited neural

resources are frequently reallocated to aid auditory activities in individuals with mild ARHL, depleting neural resources available to perform other cognitive tasks. Given that cognitive resources are domain-general, inhibitory control changes in ARHL might be modality-independent. Recently, it has been postulated that social isolation might also mediate the link between ARHL and cognition (Chern & Golub, 2019; Shukla et al., 2020). Older adults with mild ARHL may withdraw from social interactions due to communication difficulties, especially in noisy settings (Divenyi et al., 1997; Dubno et al., 1964). Many studies have shown links between increased social isolation and poor cognitive control in older adults (see Doll-Wilhelm, 2021; Evans et al., 2018 for systematic reviews). Thus, it is plausible that social isolation may alter cognitive control abilities in individuals with mild ARHL. However, it is important to note that our study did not gather information related to social isolation in our groups to examine whether there were differences between the mild ARHL and NH control groups to examine this connection (See **Figure 5.2** for illustration on mechanisms). Studies in this dissertation were not designed to test any of the theoretical hypotheses. The delineation of which hypothesis relates best to cognitive control changes in ARHL can inform clinical interventions to alleviate the risk of cognitive alterations in ARHL. Future studies could use sophisticated analyses such as structural equation modeling, combining behavioral, neuroimaging, and electrophysiological data to better understand cognitive control changes in ARHL.

SiN Recognition and Cognitive Flexibility, Inhibitory Control

Findings from studies two and three (Chapter 3,4) showed that SiN recognition is associated with cognitive flexibility and inhibitory control. Specifically, older adults with worse SiN recognition had greater behavioral impairments on Trial Making Test-B and letter fluency tasks of cognitive flexibility; and worse performance on Go/NoGo inhibitory control tasks

(Chapter 3). Additionally, those with ARHL that experienced worse SiN recognition issues tended to exert greater neural effort to perform the inhibitory control task, as indexed by greater P3 amplitude on NoGo trials (Chapter 4). The relationship between SiN recognition and cognition has received considerable attention over the past two decades. Two theoretical frameworks, the Framework for Understanding Effortful Listening (FUEL; Pichora-Fuller et al., 2016) and the Ease of Language Understanding Model (ELU; Rönnberg et al., 2013, 2019) have highlighted the role of cognitive processes in SiN recognition. Broadly, they propose that in the case of a degraded speech signal (e.g., background noise), individuals are unable to effectively match the speech signal to their mental representations, thereby resulting in engagement of top-down cognitive resources. Particularly, involvement of working memory, which allows storing/updating of the continuous speech signal has been demonstrated by many (Kim et al., 2020; see Rönnberg et al., 2010, 2019 for a review). Similarly, cognitive flexibility and inhibitory control appears to play a supportive role in SiN recognition. It is plausible that our participants with mild ARHL who experienced greater SiN challenges, recruited more cognitive flexibility to switch between the multiple mental representations of words evoked by the speech signal, as well as engaged more inhibitory control to suppress the irrelevant background noise to aid correct matching of the incoming words. Furthermore, as we factored out pure-tone average, it seems that the link between SiN recognition and cognitive flexibility, inhibitory control goes beyond peripheral hearing deficits. Our findings extend the work on the interplay between SiN recognition and top-down cognitive resources, by demonstrating involvement of cognitive flexibility and inhibitory control in central hearing functions, particularly for complex listening situations. Future research can more intricately determine the role of cognitive control in central

hearing by using other well-validated tests of central hearing, including Dichotic Digit Test and Synthetic Sentence Identification tests.

5.2. Clinical Implications and Future Directions

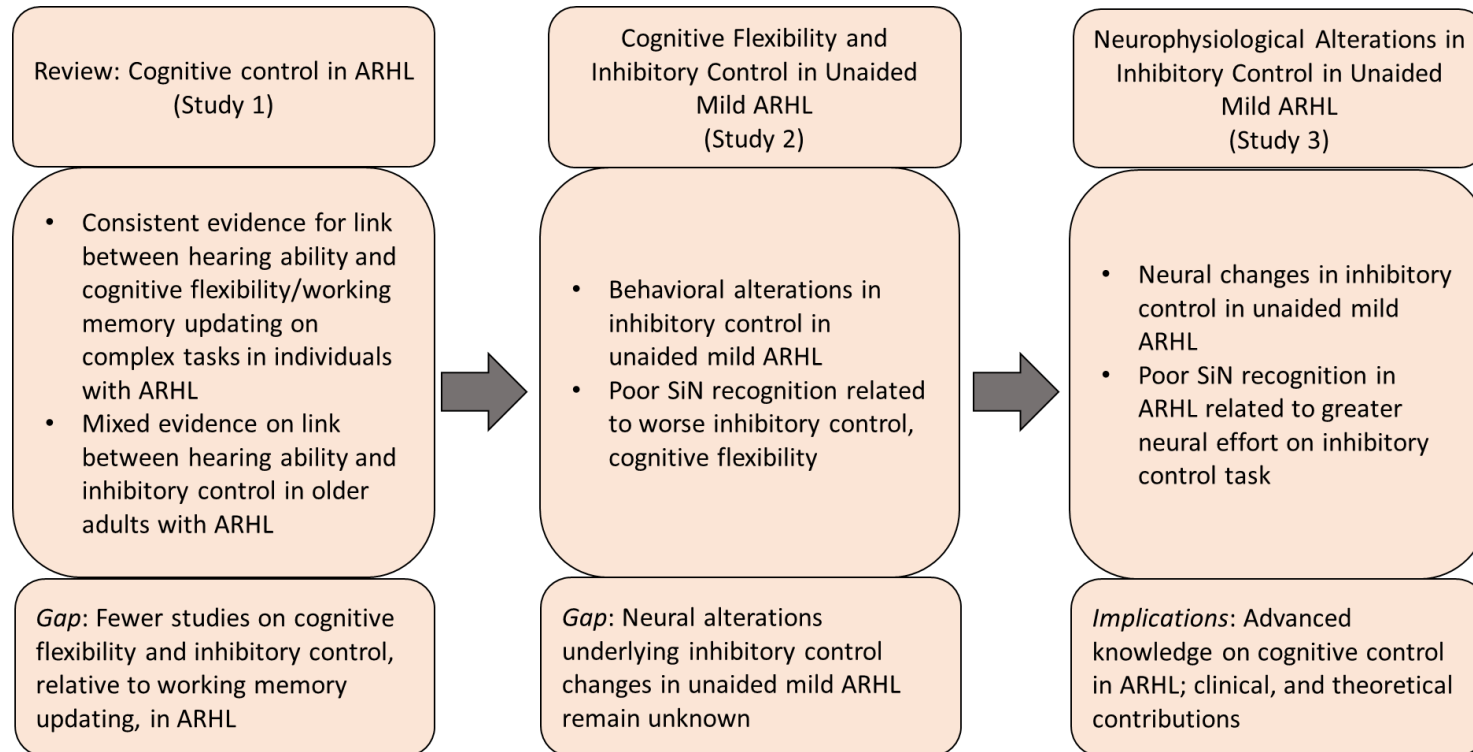
Individuals with mild ARHL often do not seek amplification or are inconsistent users of amplification (Chien & Lin, 2012). The sensory-deprivation hypothesis suggests that long-term hearing loss could lead to irreversible cognitive changes (CHABA, 1988; Lindenberger & Baltes, 1994; Oster, 1976), which could potentially increase one's risk for dementia. To prevent the progression of behavioral/neurophysiological cognitive changes in unaided mild ARHL, one potential solution could be consistent use of amplification. The Aging and Cognitive Health Evaluation in Elders (ACHIE) clinical trial, one of the largest on use of hearing aids for dementia prevention, is currently underway. While results of this trial will not be available until 2022-2023, their pilot study demonstrated that hearing aid use had a positive effect on cognitive performance (Deal et al., 2018). Also, future research should examine the impact of different technological advances in hearing aids, including sophisticated noise reduction techniques, on reduction of cognitive burden during challenging listening conditions. Perhaps bottom-up support from sophisticated hearing aids can “free” the cognitive resources engaged to aid SiN recognition in individuals with ARHL. Additionally, top-down support could alleviate the cognitive decline in individuals with mild ARHL. Provision of cognitive strategies and/or cognitive training could help in mitigating the risk of cognitive impairment in older adults with ARHL, especially when complemented with routine audiological management (hearing aids, auditory training). In fact, emerging evidence suggests that auditory and cognitive training are effective for improving cognition in adults with ARHL (Lawrence et al., 2018). However, the body of work on cognitive intervention in ARHL is scant and significant amount of research is

needed. Particularly, future studies should determine which cognitive processes are the most amenable to positive treatment in individuals with ARHL. Finally, randomized controlled trials with long-term follow-up assessments are needed to determine whether bottom-up, top-down interventions, or a combination of both reduces or potentially reverses the risk of dementia in ARHL.

5.3. Figures

Figure 5.1.

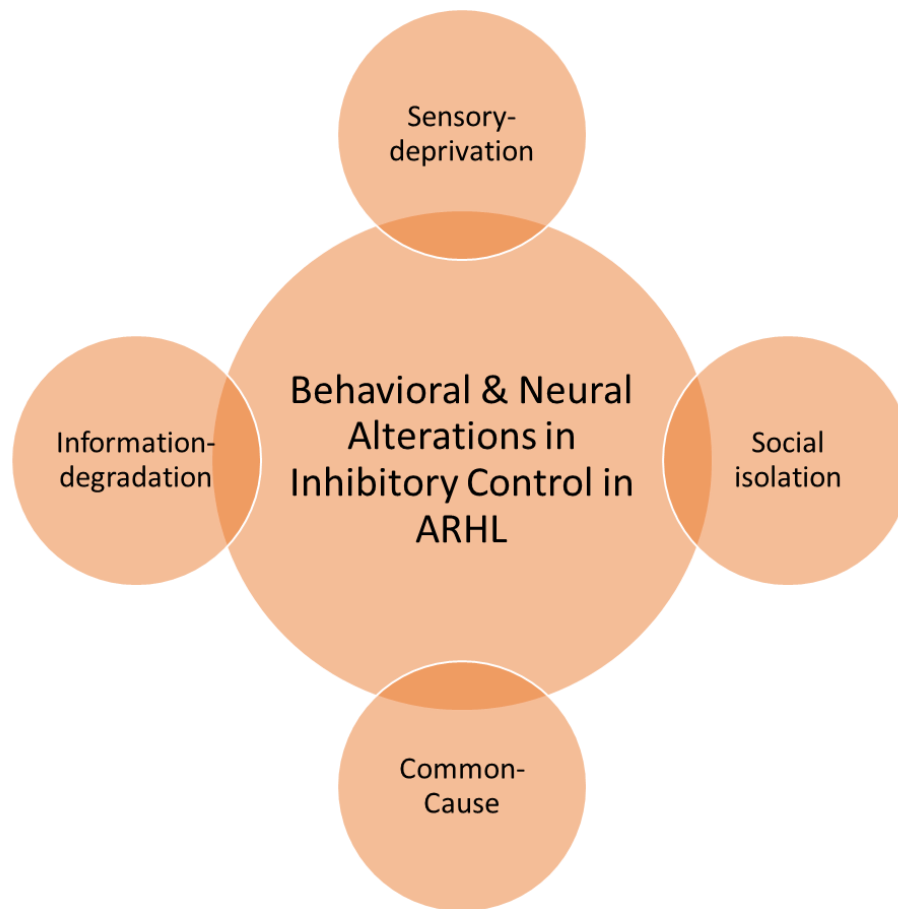
Illustration Depicting Summary of Studies in this Dissertation



Note. First row of boxes show the focus of each study in the dissertation; second row represents main findings; and final row highlights gap of each study, except for study 3 which shows implications of findings. The findings of each study informed the next study, represented by the block arrows. ARHL: Age-Related Hearing Loss; SiN: Speech-in-Noise.

Figure 5.2.

Possible Mechanisms for Inhibitory Control Alterations in Age-Related Hearing Loss



5.4. References

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