COGNITIVE FLEXIBILITY AND INHIBITORY CONTROL

IN ADULTS WITH HEARING LOSS

A DOCTORAL THESIS

Submitted to the University of Mysore,

for the award of the degree of

Doctor of Philosophy (PhD) in Speech Language Pathology

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CERTIFICATE

This is to certify that thesis entitled "**Cognitive Flexibility and Inhibitory Control in Adults with Hearing Loss"** submitted by Ms. Pooja C for the degree of Doctor of Philosophy (Speech Language Pathology) to the University of Mysore, Mysuru was carried out at the All India Institute of Speech and Hearing, Mysuru.

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DECLARATION

I declare that this thesis entitled "**Cognitive Flexibility and Inhibitory Control in Adults with Hearing Loss**" submitted herewith for the award of the degree of Doctor of Philosophy (Speech Language Pathology) to the University of Mysore, Mysuru is the result of work carried out by me at the All India Institute of Speech and Hearing, Mysuru, under the guidance of Dr. Hema N, Assistant Professor in Speech Language Sciences, All India Institute of Speech and Hearing, Mysuru. I further declare that the results of this work have not been previously submitted for any other degree.

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As I complete this resubmission, I carry forward an important lesson: the importance of knowledge, honesty in effort, and staying true to oneself. I commit to becoming a better, more authentic version of myself - both as a researcher and as a person.

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ABSTRACT

Age-Related Hearing Loss (ARHL) is a prevalent sensory issue that typically emerges in mid-life and progresses with age, significantly impacting both ears symmetrically. Beyond being a well-established risk factor for dementia, hearing loss is also associated with adverse outcomes such as social isolation, depression, and cognitive decline. Given the global aging population, the need to understand brain changes related to aging, particularly dementia, is increasingly crucial. Identifying modifiable risk factors like hearing loss could delay the onset of dementia, particularly in mid-life when hearing loss is a substantial contributor to dementia cases. This study investigates cognitive flexibility and inhibitory control in adults aged 45 to 55 years with mild bilateral sensorineural hearing loss, aiming to identify early cognitive changes in midlife due to hearing loss. The research employed a standard group comparison design involving 19 adults with hearing loss and 21 adults with normal hearing who underwent audiometric and cognitive assessments, including verbal fluency tests, the Trail Making Test-B, the Stroop test, and the Go/NoGo test. The results demonstrated significant differences between the two groups across multiple cognitive tasks, suggesting that even mild hearing loss may increase the risk of cognitive decline. The findings underscore the importance of integrating cognitive assessments into hearing evaluations to address both auditory and cognitive health comprehensively. Early intervention strategies are crucial to mitigating cognitive impairment associated with hearing loss. The study also highlights the need for a multidisciplinary approach in future research, incorporating behavioral, neuroimaging, and electrophysiological methods to fully understand the cognitive changes associated with hearing loss and to develop effective interventions

Chapter 1

Introduction

Among all sensory deficits linked to aging, the most notable decline in humans is typically in hearing (Howarth & Shone, 2006). Hearing loss in adults commonly presents as a progressive, bilateral, symmetrical sensorineural impairment. This type of hearing loss is also referred to as Age-Related Hearing Loss (ARHL) (Gates & Mills, 2005; ISO, 2000). It can be attributed to a combination of physical and environmental factors, along with genetic predisposition. Additionally, increased vulnerability from physiological stressors and modifiable lifestyle behaviors sustained throughout life can contribute to ARHL (Agrawal et al., 2009). The most pronounced hearing loss typically occurs at higher frequencies, initially affecting the detection of high-pitched sounds. The onset typically begins in the fourth decade of life. However, the sharpest increase in prevalence occurs in individuals aged 80 years and older, with 50% to 80% ultimately affected by this condition (Cruickshanks et al., 1998). According to the Global Burden of Disease Study (2015), hearing loss ranks as the fifth most prominent cause of years lived with disability globally. As the population continues to age, leading to increased functional limitations, its impact is expected to rise even further.

Hearing loss is conventionally defined by audiometric thresholds, which represent the lowest level of sound (measured in decibels hearing level [dB HL]) that an individual can detect across various frequencies in a sound-attenuated room. Hearing thresholds are commonly assessed through pure-tone audiometry, a test that determines the lowest detectable levels of pure tones across various frequencies. The majority of such cases involve sensorineural hearing loss which is characterized by the degeneration of outer and inner hair cells located within the cochlea. Among these, the

inner hair cells play a crucial role in transducing auditory signals. The atrophy typically initiates at the basal end of the cochlea and gradually progresses towards the apex over time. This basal atrophy results in the characteristic high-frequency hearing loss associated with sensory ARHL (Liberman & Kujawa, 2017).

It is commonly known that hearing loss is prevalent in older adults and sensorineural hearing loss is a widespread occurrence on a global scale (Stevens et al., 2013). The prevalence of hearing loss doubles with each successive decade of increased age and mostly begins during mid-life—approximately 27% of adults in their mid-life experience hearing loss (Chen et al., 2014). However, there is a scarcity of research highlighting the increasing prevalence of hearing loss in mid-life. Such findings present potential opportunities for early intervention to mitigate the significant future impact of ARHL (Wang et al., 2019). Hearing loss in mid-life not only acts as a potential risk factor for dementia (Del Vecchio et al., 2023) in older adults by influencing changes in brain structures but is also associated with increased late-life atrophy over time, particularly in specific temporal lobe structures (Armstrong et al., 2019).

Further, hearing loss is linked with notable psychological and medical morbidity, contributing to issues such as social isolation, frailty, depression, and cognitive decline (Kamil et al., 2016; Lin et al., 2011; Rutherford et al., 2018). Extensive evidence suggests that hearing loss adversely affects both physical and mental health, cognition, independence, social interaction, and overall quality of life. Furthermore, hearing loss has also been associated with the early signs of dementia and Alzheimer's disease (AD) (Cherko et al., 2016; Cosetti & Lalwani, 2015; Taljaard et al., 2016). Extensive research has highlighted a significant association between hearing loss and dementia, suggesting that auditory deficits may contribute to cognitive decline

through mechanisms such as social withdrawal, increased cognitive load, and reduced neural stimulation.

1.1 Hearing loss and dementia

With a growing elderly population, it's crucial to deepen the understanding of the neurological changes that accompany aging. This is pertinent not only concerning "pathological" aging, where the onset of numerous neurodegenerative disorders is predominantly seen in older individuals (given that age serves as the primary risk factor for conditions like AD) but also regarding what's deemed as "normal" or "healthy" aging. Particularly noteworthy is the prevalence of "age-related cognitive decline" among a significant portion of older adults which is distinct from dementia and has an incidence rate 70% higher than dementia alone. It is crucial to view cognition as a continuum as adults age, as this perspective enables us to enhance our understanding of both healthy and pathological cognitive decline. On one end of the spectrum lies healthy cognitive aging, while on the opposite end lies pathological aging, ultimately leading to dementia. Thus, dementia can be perceived as another end of the continuum, representing severely affected cognition. Dementia is a disease closely associated with aging and severely affects elderly adults worldwide (Alzheimer's Association, 2016; Prince et al., 2014).

Dementia results in disability and dependency, affecting not only the individuals but also their caregivers, imposing a significant burden on families and the global economy alike. The prevalence of dementia is projected to increase rapidly by the year 2050, resulting in approximately 1 in 85 individuals worldwide living with the disease (Patterson, 2018; WHO, 2017). Interventions that could modestly delay the onset (Tom et al., 2015) and progression of the disease by just one year would

potentially lead to a reduction of nearly 9.2 million dementia cases by the year 2050 (Brookmeyer et al., 2007). Regrettably, no known interventions currently demonstrate such effectiveness in controlling the disease. The duration of dementia represents the period from onset to death, as unfortunately, recovery is not feasible. Hence, identifying potential risk factors that can be targeted for preventive measures is essential.

To date, there are twelve potentially modifiable risk factors for dementia that have been systematically listed according to stages of life (Livingston et al., 2020). According to the currently established risk factors, less education has been identified as a risk factor in early life (age <45 years). In later life (age >65 years), smoking, depression, social isolation, physical inactivity, diabetes, and air pollution contribute to the risk factors. Mid-life (age between 45 – 65 years) risk factors include hearing loss, traumatic brain injury, hypertension, alcohol, and obesity.

In recent studies, a strong link has been established between dementia and hearing loss, with the latter being identified as an independent but also a promising modifiable risk factor for incident dementia (Amieva et al., 2015; Deal et al., 2017; Fu et al., 2022; Gallacher et al., 2012; Gao et al., 2020; Golub et al., 2020; Lin et al., 2011a, b; Quaranta et al., 2014; Rong et al., 2020; Thomson et al., 2017). When considering this in the context of different countries, the number of individuals with dementia in low and middle-income countries (LMIC) is increasing at a faster rate compared to high-income countries (HIC), primarily due to rising life expectancy and a higher burden of risk factors.

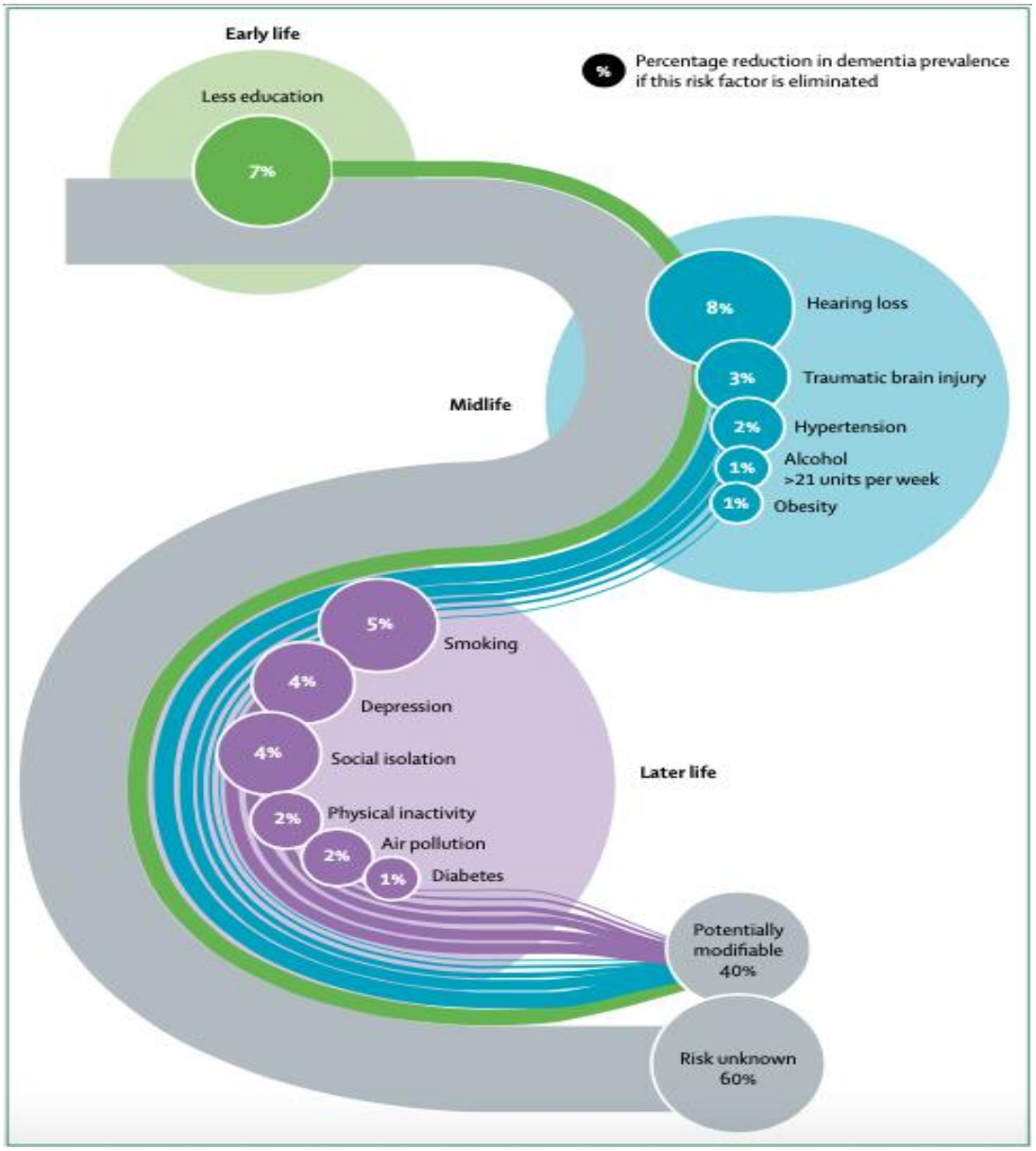
The LANCET Commission (2017) estimated the population attributable fraction (PAF) for the modifiable risk factors of dementia where PAF refers to the percentage reduction in new cases of a specific condition over a given period of time if

a particular risk factor were to be entirely eliminated from the population. Calculations considering country-specific prevalence of the potentially modifiable risk factors indicate a PAF of 41% in India. This suggests a higher potential for dementia prevention in India than in global estimates. These findings emphasize the importance of addressing modifiable risk factors in India to reduce the burden of dementia. While early-life factors, like low education, impact the cognitive reserve, risk factors during midlife and old age contribute to age-related cognitive decline and may trigger the onset of neuropathological changes.

There are more compelling reasons that underscore the importance of directing attention towards adults in mid-life. Firstly, most of the health conditions contributing to a risk factor for dementia start in mid-life such as obesity, hypertension, cardiovascular disease, and other metabolic disorders. Secondly, adults with high rates of hypertension exhibit an elevated risk of developing dementia at a younger age (Adelman et al., 2009, 2011; Laditka et al., 2008). Thirdly, the rising rates of obesity and its related health problems during mid-life are projected to result in a significant increase in dementia (Loef & Walach, 2013). Further, the UK National Institute of Health and Care Excellence (NICE) and the US National Institutes of Health (NIH) identify hearing loss as one of the potentially modifiable risk factors that occur during midlife. Hearing loss accounted for 23.0% which was the highest PAF of all other individual risk factors considered, with the highest prevalence and relative risk in mid-life. Livingston et al. (2020) proposed an estimation indicating that approximately 40% of dementia instances may be attributed to a cohort of twelve conceivably modifiable risk factors. Among the risk factors considered across all stages of life, hearing loss accounts for the highest proportion, at 8% as depicted in Figure 1.1.

Figure 1.1

Population Attributable Fraction of Potentially Modifiable Risk Factors for Dementia



Note. Adapted from "Dementia prevention, intervention, and care: 2020 report of the Lancet Commission", by Livingston, G., Huntley, J., Sommerlad, A., Ames, D., Ballard, C., Banerjee, S., Brayne, C., Burns, A., Cohen-Mansfield, J., Cooper, C., Costafreda, S. G., Dias, A., Fox, N., Gitlin, L. N., Howard, R., Kales, H. C., Kivimäki, M., Larson, E. B., Ogunniyi, A., Orgeta, V., … Mukadam, N, 2020, *Lancet (London, England)*, *396*(10248), Figure 7 (https://doi.org/10.1016/S0140-6736(20)30367-6). CC BY.

For decades, researchers have independently studied hearing loss and cognitive impairment in older adults. However, what might be even more intriguing is the connection between hearing and cognition, as well as the potential mechanisms that underlie this relationship (Gallacher, 2004). In recent years, there has been a notable increase in research highlighting a significant relationship between hearing loss and cognition. This relationship has been observed both cross-sectionally (Jupiter, 2012; Lin, 2011; Lin et al., 2011; Pearman et al., 2000) and longitudinally (Kiely et al., 2012; Lin et al., 2013; Valentijn et al., 2005). For instance, in a secondary analysis of data from the U.S. Aging, Demographics, and Memory Study, Gure and colleagues (2013) discovered that about 42% of individuals diagnosed with dementia and approximately 44% of individuals with cognitive impairment without dementia experienced significant hearing issues.

Additionally, in a cross-sectional study (Lin, 2011) and two longitudinal studies (Lin et al., 2011; Lin et al., 2013), it was found that peripheral hearing loss was significantly linked to accelerated cognitive decline, incident cognitive impairment, and the onset of dementia. Both cross-sectional and longitudinal studies have reported significant associations between peripheral hearing and scores on global cognitive assessments (Kiely et al., 2012; Lin et al., 2011; Lin et al., 2013), as well as measures of memory (Lin et al., 2011; Pearman et al., 2000; van Boxtel et al., 2000) and executive functioning (Lin, 2011; Lin et al., 2011; Lin et al., 2013). Among the various cognitive tests utilized to establish the relationship between hearing loss and cognitive decline, executive functions are frequently included (Harrison Bush et al., 2015; Humes et al., 2010).

1.2 Executive functions

Executive functions (EF), alternatively termed executive control or cognitive control, encompass a set of higher-order cognitive processes required during tasks demanding focused attention. There is a consensus that EF comprises three processes that are also called the core EF, namely, working memory, cognitive flexibility, and inhibitory control (Diamond, 2013; Miyake et al., 2000). Below, each of the core EFs is elaborated upon according to Diamond (2013) and Miyake and colleagues (2000).

1.2.1 Working memory

The primary function of EF revolves around the continuous monitoring and updating of information within the working memory. This dynamic process involves the ongoing assessment of incoming information for relevance to the current task at hand and the subsequent revision of the contents held in working memory. By constantly updating the information in working memory, individuals can adaptively respond to changing environmental demands and effectively engage in goal-directed behaviour. The working memory or updating function necessitates the monitoring of incoming information for its relevance to the current task. EF also involves appropriately revising the items held in working memory by replacing old or irrelevant information with newer, more pertinent information (Morris & Jones, 1990).

Smith and Jonides (1997) proposed that this process may involve temporal tagging to keep track of the information. This mechanism aids in efficiently managing working memory by replacing outdated or irrelevant information with newer, more relevant information. The essence of working memory lies in the requirement to actively manipulate relevant information rather than passively store it. This active manipulation enables individuals to engage with and process information dynamically,

facilitating cognitive tasks such as problem-solving, decision-making, and comprehension.

Recent neuroimaging studies have shown a disparity between the regions associated with passive storage and those involved in active updating. Working memory is frequently associated with the dorsolateral part of the prefrontal cortex (Goldman-Rakic, 1996; Smith & Jonides, 1999). While the mere retention of information is linked to premotor regions of the frontal cortex and the parietal lobes, the more intricate updating function, as exemplified by tasks like the N-back task, is closely associated with the dorsolateral prefrontal cortex. This distinction sheds light on the neural mechanisms underlying the processes of passive memory and active manipulation of memory (Smith & Jonides, 1997). A meta-analysis of 60 PET and fMRI studies identified key brain regions involved in working memory. The superior frontal cortex (BAs 6, 8, 9) supports continuous updating and temporal order, while the ventral frontal cortex (Right BAs 10, 47) is active in manipulation tasks. Left frontal regions dominate in verbal WM with low executive demand, whereas right frontal regions show increased activation in spatial WM with high executive demand. The posterior parietal cortex (BA 7) is engaged in all executive functions, and the medial prefrontal cortex (BA 32) is involved in selective attention during storage tasks (Christophel et al., 2017). Hence, distinct frontal and parietal brain regions support different aspects of working memory, with lateralization based on task type and executive demand.

1.2.2 Cognitive flexibility

Cognitive flexibility revolves around transitioning between various tasks, operations, or mental sets. It is also known as attention-switching, task switching, and set-shifting. In other words, cognitive flexibility allows an individual to disengage from an irrelevant task set, followed by subsequent active engagement with a relevant task set. This ability is crucial in comprehending cognitive control scenarios that demand individuals to shift between tasks (Monsell, 2021) adeptly. Although the process looks simpler on the surface, it is essential to overcome proactive interference or negative priming resulting from the prior execution of a distinct operation or adaptation of the brain to carry out activities in a set pattern. For instance, during a verbal fluency task if the initial instruction was to list items from the category 'animals' and subsequently the task required to switch between naming animals and fruits, individuals may persist in mentioning animal names and struggle to inhibit this response while switching between the two categories. Such tasks require effortful attention and inhibitory control to provide accurate responses. Hence, variations in cognitive flexibility among individuals may not solely mirror their capacity to activate and deactivate relevant task sets. Instead, it could also, or perhaps predominantly, signify their capability to execute a new operation in the presence of proactive interference by exerting inhibitory control.

1.2.3 Inhibitory control

Inhibitory control, the third core process of EF pertains to an individual's capacity to intentionally suppress dominant, automatic, or prepotent responses when required. This ability to inhibit habitual or instinctive reactions plays a crucial role in regulating behaviour and facilitating adaptive responses to situational demands. By exercising inhibitory control, individuals can override impulsive tendencies and instead

engage in more thoughtful and goal-oriented actions. This EF is essential for navigating complex situations, adhering to rules and norms, and achieving objectives despite immediate temptations or distractions. A classic example of an inhibition task is the Stroop task, wherein individuals must suppress or override the inclination to produce a dominant or automatic response (such as naming the color word). This form of inhibition is frequently categorized as an EF. In the Stroop task, participants are presented with color words printed in incongruent ink colors (e.g., the word "green" printed in red ink), and they are instructed to name the ink color while ignoring the word itself. The task requires individuals to inhibit the automatic tendency to read the word and instead focus on the color information, thus demonstrating their capacity for cognitive control and inhibition of prepotent responses. By examining performance on tasks like the Stroop task, researchers have gained insights into individuals' ability to regulate their attention and suppress interfering information, contributing to the understanding of EF.

The above-mentioned functions become crucial in situations where relying on automatic responses, instinct, or intuition would be inappropriate or inadequate (Burgess & Simons, 2005; Espy, 2004; Miller & Cohen, 2001). To use EF is to exert effort, as it is more convenient for individuals to operate on autopilot and persist in their established behaviors rather than adapting to a demanding situation. Hence, EF can be stated as controlling mechanisms that regulate the functioning of diverse cognitive processes, thus governing the dynamics of complex human cognition. EF are important cognitive processes that are essential for managing complex tasks, problem-solving, decision-making, and adapting to new situations. As individuals age, there is often a noticeable decline in executive functioning abilities (Idowu & Szameitat, 2023). This decline can manifest as difficulties in organizing thoughts, maintaining attention,

switching between tasks, and inhibiting irrelevant information or responses (Cabeza et al., 2004; Salthouse, 2009, 2012). There are several studies to suggest that a decline in certain aspects of EF represents a significant risk factor for the impending onset of cognitive decline leading to dementia (Lindenberger et al., 2001; Sheft et al., 2015). Research has also shown that deficits in EF are closely associated with various forms of dementia, including AD and vascular dementia (Urbanowitsch et al., 2015; Wongupparaj et al., 2015). Individuals with dementia often exhibit impairments in planning, problem-solving, multitasking, and maintaining goal-directed behavior, all of which are core components of EF (Vaughan & Giovanello, 2010). Initially, Baddeley and colleagues identified that selective impairment of the central executive component within working memory is a notable characteristic of AD (Baddeley et al., 1986; Baddeley et al., 1991). Later, studies by Binetti et al. (1996), Bondi et al. (2002), and Lafleche and Albert (1995) consistently showed that the onset of executive dysfunction typically precedes impairments in language or cognition.

Research by Albert et al. (2007), Bondi et al. (1994), Elias et al. (2000), Jacobs et al. (1995), and Rapp and Reischies (2005) have shown that cognitive tests with substantial EF requirements are among the most helpful for predicting which nondemented older individuals will later develop dementia. These findings clearly underscore the critical role of EF in the early detection and prediction of cognitive decline leading to dementia. Moreover, longitudinal studies have demonstrated that executive dysfunction may precede the clinical onset of dementia by several years, serving as an early marker or prodromal symptom of cognitive decline (Powell et al., 2022).

Furthermore, neuroimaging studies have revealed structural and functional changes in brain regions implicated in executive functioning, such as the prefrontal cortex, anterior cingulate cortex, and dorsolateral prefrontal cortex, in individuals with dementia (Johnson et al., 2021). These alterations may contribute to the observed deficits in executive control and cognitive decline. Given the crucial role of EF in daily functioning and cognitive health, monitoring changes in these abilities over time may serve as an important indicator for identifying individuals at risk for cognitive decline and implementing early intervention strategies as early as mid-life.

1.3 Need for the study

1.3.1 Need to consider adults in mid-life between 45 to 55 years of age

Research suggests that hearing loss can be linked to faster cognitive decline, but many studies have focused on elderly age and beyond. According to the revised standards for the classification of age groups by the World Health Organization (2015), middle age is defined as 44 to 60 years, elderly age as 60 to 75 years, and senile age as 75 to 90 years. However, the age group spanning from 45 to 64 years old have exhibited the highest count of individuals experiencing hearing impairment (Agrawal et al., 2008). Hence, middle age may represent a critical window where subtle cognitive changes start to manifest. To date, there is limited data that attempted to identify subtle cognitive changes that occur in early mid-life adults (between 45 to 55 years of age) with hearing loss (Merten et al., 2020). If cognitive decline begins in middle age due to hearing loss, this period presents an opportunity for prevention. Intervening earlier, before significant cognitive damage occurs, could reduce the risk of developing cognitive impairments later in life.

For instance, Armstrong et al. (2019) investigated the link between midlife hearing impairment and late-life brain volume loss, focusing on the temporal lobe. Using MRI data, they analyzed brain volume changes in older adults and found that individuals with midlife hearing impairment showed greater atrophy in the temporal lobe compared to those with normal hearing. These findings suggest that hearing loss in midlife may contribute to neurodegeneration, emphasizing the importance of early intervention for hearing impairment to potentially reduce the risk of brain atrophy. Such studies shed light on the vulnerability of brain regions related to cognition and emphasizes that testing in midlife helps in pinpointing when these changes begin, offering insights into how hearing loss accelerates neurodegeneration. It has been observed that 55 years is the youngest mean age at which the presence of hearing loss increases the risk of cognitive decline (Gallacher et al., 2012). Therefore, the present study aimed to investigate whether any changes occur before this age, focusing on adults aged between 45 to 55 years.

1.3.2 Need to consider adults with bilateral mild sensorineural hearing loss

The current understanding regarding the relationship between hearing loss and cognitive impairment suggests that the association is first seen with mild hearing loss (Lin, 2011). At mild levels of hearing loss and beyond, the risk of cognitive impairment escalates in a dose-dependent manner. It is crucial to detect cognitive changes in individuals with mild hearing loss as this marks the initial stage where cognitive changes begin to manifest. In a comprehensive cross-sectional study involving 6451 individuals, demographically representative of the US population averaging 59.4 years of age, a noteworthy trend was observed. Cognitive performance exhibited a decline with each 10-decibel reduction in hearing capacity. Even when hearing problems were

not severe enough to be clinically diagnosed, they still affected cognitive abilities, showing a clear link between mild hearing loss and lower cognitive function (Golub et al., 2020).

Cohort studies indicate that even mild levels of hearing loss, defined as the pure-tone average of hearing thresholds at 0.5, 1, 2, and 4 kHz within the range of 25–40 dB, can increase the likelihood of cognitive decline among individuals who are initially cognitively intact but have hearing impairment (Gallacher et al., 2012; Lin et al., 2011). A study that focused on understanding the association of subclinical hearing loss with cognitive performance found that among adults with slight hearing loss, declining hearing was linked to declining cognition (Golub et al., 2020). In a longitudinal study of community-dwelling older adults by Alattar et al. (2020), the association between hearing impairment and long-term cognitive decline was investigated. Specifically, even mild hearing impairment was linked to steeper declines in cognitive function, with more pronounced effects observed in individuals with moderate to severe impairment.

Findings from such studies have underscored the importance of early screening may offer some protection against cognitive decline associated with mild hearing impairment. Another study exploring the association between hearing loss and cognitive function found that bilateral hearing loss was associated with a higher prevalence of cognitive disorder compared to unilateral hearing loss. Individuals with bilateral hearing loss exhibited a higher risk of cognitive disorder than those with unilateral hearing loss or normal hearing underscoring that bilateral hearing loss is particularly associated with poorer cognitive outcomes (Lee et al., 2021). Hence, the present study considered adults with bilateral mild sensorineural hearing loss to understand the effects of hearing loss on cognitive control at its earliest stage.

1.3.3 Need to consider Cognitive flexibility and Inhibitory control

Although cognitive decline is predominantly present in older adults, studying these changes with sensitive tests such as EF tests in middle-aged adults can provide valuable insights into cognitive aging and the early detection of cognitive decline. By understanding how EF changes in middle-aged adults, researchers can better identify risk factors and develop interventions aimed at preserving cognitive function in older age. Therefore, while the focus on elderly adults is understandable, research on EF in mid-aged groups is important for a comprehensive understanding of cognitive health and aging.

Since working memory remains relatively unaffected in the early stages and is researched widely, it becomes essential to explore other components of EF including cognitive flexibility and inhibitory control. For instance, a study investigated the impact of mild to moderate age-related hearing loss on working memory and related cognitive functions in older adults. Using fMRI during a 0-back and 2-back working memory task, the study examined neural activation in frontoparietal networks in 19 hard-of-hearing and 19 normal-hearing participants. Cognitive flexibility was assessed using the Comprehensive Trail Making Test. Results showed no differences in frontoparietal neural activation or working memory performance between the groups. However, hard-of-hearing participants exhibited reduced cognitive flexibility. These findings suggested that while neural signatures of working memory remain intact in early stages of hearing loss whereas, cognitive flexibility plays a critical role in compensating for auditory challenges, emphasizing its importance in understanding and addressing hearing-related cognitive changes (Rosemann & Thiel, 2020). The present study

utilized verbal fluency tasks and Trail making test-B to assess cognitive flexibility and used the Stroop and Go/NoGo tasks to assess inhibitory control.

In summary, given the potential impact of hearing loss on cognitive function, especially in midlife when cognitive decline may begin, evaluating EF can provide valuable insights into the cognitive status of individuals with hearing loss. Hence, assessing EF, such as cognitive flexibility and inhibitory control, in midlife adults with bilateral mild sensorineural hearing loss is crucial. It has also been suggested that individuals with hearing loss rely heavily on executive functions, which may leave other cognitive without enough support, potentially leading to cognitive strain in the long run (Guglielmi et al., 2020). Early identification of any deficits in these areas can inform intervention strategies aimed at preserving cognitive function and enhancing the overall quality of life.

1.4 Aim of the study

To investigate the cognitive flexibility and inhibitory control in adults with hearing loss.

1.5 Objectives of the study

1. To compare the performance on Verbal fluency task in terms of accuracy between adults with hearing loss and neurotypical adults.
    a. To compare the performance on semantic fluency in terms of accuracy between adults with hearing loss and neurotypical adults.
    b. To compare the performance on phoneme fluency in terms of accuracy between adults with hearing loss and neurotypical adults.

c. To compare the performance on alternate fluency in terms of accuracy between adults with hearing loss and neurotypical adults.

2. To compare the performance on Trail making test B in terms of completion time between adults with hearing loss and neurotypical adults.

3. To compare the performance on the Stroop task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults.

    a. To compare the performance in terms of accuracy between adults with hearing loss and neurotypical adults.

    b. To compare the performance in terms of average reaction time between adults with hearing loss and neurotypical adults.

    c. To compare the performance in terms of reaction time in congruent and incongruent conditions between adults with hearing loss and neurotypical adults.

    d. To compare the performance on Stroop effect between adults with hearing loss and neurotypical adults.

4. To compare the performance on the Go/NoGo task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults.

    a. To compare the performance on the Go/NoGo task in terms of accuracy between adults with hearing loss and neurotypical adults.

    b. To compare the performance on the Go/NoGo task in terms of reaction time between adults with hearing loss and neurotypical adults.

5. To study the relationship between outcome measures of Verbal fluency test, Trail making test B, Stroop task and Go/NoGo task.

6. To study the association between groups and health & lifestyle related factors.

1.6 Hypotheses of the study

The following null hypotheses were considered for the study

1. There is no statistically significant difference in the performance on verbal fluency task in terms of accuracy between adults with hearing loss and neurotypical adults.

    a. There is no statistically significant difference in the performance on semantic fluency in terms of accuracy between adults with hearing loss and neurotypical adults.

    b. There is no statistically significant difference in the performance on phoneme fluency in terms of accuracy between adults with hearing loss and neurotypical adults.

    c. There is no statistically significant difference in the performance on alternate fluency in terms of accuracy between adults with hearing loss and neurotypical adults.

2. There is no statistically significant difference in the performance on Trail making test-B in terms of completion time between adults with hearing loss and neurotypical adults.

3. There is no statistically significant difference in the performance on the Stroop task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults.

    a. There is no statistically significant difference in the performance in terms of accuracy between adults with hearing loss and neurotypical adults.

    b. There is no statistically significant difference in the performance in terms of average reaction time between adults with hearing loss and neurotypical adults.

    c. There is no statistically significant difference in the performance in terms of reaction time in congruent and incongruent conditions between adults with hearing loss and neurotypical adults.

    d. There is no statistically significant difference in the performance on the Stroop effect between adults with hearing loss and neurotypical adults.

4. There is no statistically significant difference in the performance on the Go/NoGo task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults.

    a. There is no statistically significant difference in the performance on the Go/NoGo task in terms of accuracy between adults with hearing loss and neurotypical adults.

b. There is no statistically significant difference in the performance on the Go/NoGo task in terms of reaction time between adults with hearing loss and neurotypical adults.

5. There is no significant correlation between outcome measures of Verbal fluency test, Trail making test B, Stroop task and Go/NoGo task.

6. There is no significant association between groups and health & lifestyle related factors.

Chapter 2

Review of literature

The association between hearing loss and cognitive decline has garnered significant attention in recent research, with studies increasingly highlighting the complex interplay between these conditions. Investigations have reported that individuals with hearing impairment exhibit poorer cognitive performance compared to those with normal hearing.

One of the most initial and influential studies exploring the relationship between hearing loss and cognitive function analyzed data from the 1999 to 2002 cycles of the National Health and Nutritional Examination Survey in a nationally representative sample of older adults aged 60–69 years (n = 605) (Lin, 2011). Hearing loss was defined based on a pure tone average of hearing thresholds at 0.5, 1, 2, and 4 kHz in the better hearing ear, while cognitive testing included the Digit Symbol Substitution Test (DSST), assessing executive function and psychomotor processing. Adjusting for demographic factors and medical history, regression models revealed that greater hearing loss was significantly associated with lower DSST scores. Notably, the decline in cognitive performance associated with a 25 dB hearing loss was equivalent to that seen with an age difference of 7 years. The findings suggested an independent association between hearing loss and lower DSST scores, prompting further investigation to ascertain whether hearing loss serves as a modifiable risk factor or an early indicator of cognitive decline.

Further, Gallacher et al. (2012) explored the correlation between auditory threshold and cognitive decline, as well as dementia, involving 1,057 surviving men from the Caerphilly cohort, who were followed over 17 years to assess cognitive

outcomes. Audiometric data, including pure-tone unaided thresholds at various frequencies, were collected at baseline and after 9 years. Incident dementia was diagnosed based on DSM-IV criteria. Cognitive decline was evaluated through repeated cognitive testing using the Cambridge Cognitive Examination, Mini-Mental State Examination, Immediate and Delayed Recall Tests, Incidental Memory Test, National Adult Reading Test, Alice Heim Test, and the Choice Reaction Time Task. The results indicated that the mean age-adjusted auditory threshold across both time points was associated with both incident dementia and cognitive decline. Even after adjusting for premorbid cognitive function, the association with dementia persisted. While the study's design and long follow-up period strengthen its findings, the reliance on audiometric measures taken at only two time points may overlook fluctuations or progressive changes in hearing loss and their dynamic relationship with cognitive outcomes. Additionally, while the study adjusts for premorbid cognitive function, it does not fully account for other potential confounders, such as lifestyle factors, social isolation, or depression, which may mediate this association. These limitations highlighted the need for more frequent assessments and a broader examination of contributing factors, which is addressed by Lin et al. (2013).

This prospective observational study examined 1984 older adults from the Health ABC (Health, Aging, and Body Composition) Study, focusing on individuals without prevalent cognitive impairment at baseline. Audiometric testing was conducted in year 5 to assess hearing, and participants were followed up for 6 years. Baseline hearing was defined using a pure-tone average of thresholds at 0.5 to 4 kHz in the better-hearing ear. Cognitive testing occurred in subsequent years and included the Modified Mini-Mental State Examination (3MS) and the Digit Symbol Substitution test. Incident cognitive impairment was defined based on a 3MS score decline or reaching a score

below 80. Results showed that individuals with baseline hearing loss (pure-tone average ≥25 dB) experienced greater annual rates of cognitive decline and had a higher risk of incident cognitive impairment compared to those with normal hearing. These associations were linearly related to the severity of baseline hearing loss.

While the study by Lin et al. (2013) strengthens the evidence that hearing loss is associated with accelerated cognitive decline and incident cognitive impairment, it is limited in its scope by relying on cognitive assessments like the 3MS that may not fully capture subtle early changes or account for educational and cultural variability. This limitation emphasizes the need to explore more direct mechanisms linking hearing loss with brain changes, particularly structural alterations. To address these gaps, Lin and colleagues conducted another study in 2011, focusing on the association between hearing impairment and brain atrophy. Using magnetic resonance imaging data from the neuroimaging substudy of the Baltimore Longitudinal Study of Aging, brain volume trajectories were examined over an average of 6.4 years. They found that individuals with hearing impairment experienced accelerated atrophy in both whole brain and regional volumes, particularly in the right temporal lobe, which includes critical areas such as the superior, middle, and inferior temporal gyri and the parahippocampus. By demonstrating a direct link between hearing loss and structural brain changes, this study builds upon prior findings, addressing the need to connect peripheral hearing impairment with neuroanatomical alterations.

Along similar lines, Bush et al. (2015) conducted a study with the primary objective to explore the relationship between peripheral hearing and various domains of cognition, including processing speed, executive functions, and memory, along with global cognitive status, in older adults. A cohort of 894 older adult participants from

the Staying Keen in Later Life (SKILL) study underwent baseline evaluation, with inclusion criteria designed to encompass a diverse range of sensory and cognitive abilities. Multiple linear regression analyses were conducted to assess how peripheral hearing, measured as the three-frequency pure-tone average (PTA) in the better ear, predicted performance across cognitive measures. The study found that peripheral hearing accounted for a significant, albeit minimal, amount of variance in measures of processing speed, executive function, memory, and global cognitive status. Consistent with existing literature, the findings indicated a significant relationship between peripheral hearing and cognition, with peripheral hearing significantly associated with measures of processing speed, executive function, memory, and global cognitive status.

With studies indicating an independent association between hearing loss and poorer cognitive functioning, another study aimed to assess the prevalence of HL and cognitive impairment in a large sample of individuals aged 65 years and older while also examining the correlation between hearing function and cognitive function (Quaranta et al., 2014). A total of 488 participants, with a mean age of 72.8 years, from the Great Age Study underwent comprehensive audiological, neurological, and neuropsychological evaluations. The prevalence of hearing loss greater than 25 dB HL was 64.1%, while 25.3% reported a hearing handicap based on the Hearing Handicap Inventory for the Elderly Screening Version questionnaire. Multiple logistic regression analyses, adjusting for gender, age, and education duration, revealed a significant association between mild cognitive impairment (MCI) and hearing impairment. This study highlighted the potential for integrating auditory tests into cognitive screening protocols for early detection of cognitive decline, particularly since MCI often progresses to Alzheimer's disease.

Building on this, Pichora-Fuller (2015) reviewed the broader implications of age-related cognitive decline for hearing healthcare, emphasizing the need to incorporate cognitive considerations into audiological practice. Recognizing the significant prevalence of both hearing and cognitive impairments, particularly among the oldest older adults, the study underscored the importance of interdisciplinary collaboration and teamwork in healthcare delivery.

Similarly, Fortunato et al. (2016) conducted a comprehensive review focusing on age-related hearing loss (ARHL) and its association with accelerated cognitive decline and dementia. The review highlighted how ARHL affects multiple domains, including social relationships, motor skills, psychological well-being, and even specific brain functions and structures. The review explored the association between hearing loss and cognitive decline and the mechanisms underlying this relationship. Epidemiological and clinical studies consistently supported that hearing loss can impair communication, leading to social isolation and depression—factors known to exacerbate the risk of dementia. Conversely, diminished cognitive abilities may reduce the resources available for auditory perception, further worsening the impact of HL. Shared pathophysiological factors, such as microvascular diseases (e.g., diabetes, atherosclerosis, and hypertension), are also implicated in contributing to both HL and cognitive decline, indicating a multifactorial relationship.

Likewise, Taljaard et al. (2016) also sought to explore this relationship further by systematically reviewing the literature and conducting meta-analyses to investigate the relationship between hearing and cognition. Data from 33 studies found significant associations. Specifically, cognition was notably poorer in individuals with untreated hearing impairment compared to those with normal hearing. Moreover, the degree of

cognitive impairment correlated with the severity of hearing impairment. Importantly, hearing impairment was found to affect all domains of cognition.

Additional studies have also provided supporting evidence for the connection between hearing loss and dementia. The study by Deal et al. (2017) provides strong evidence linking moderate to severe hearing impairment (HI) with an increased risk of developing dementia in older adults over a 9-year period. In this prospective analysis utilizing data from the Health, Aging and Body Composition (Health ABC) study, the association between age-related peripheral HI and incident dementia, as well as domain-specific cognitive decline, was examined in a cohort of well-functioning adults aged 70-79 years. The study found that individuals with moderate/severe audiometric HI, compared to those with normal hearing, had a significantly increased risk of developing dementia over a 9-year follow-up period, even after adjusting for demographic and cardiovascular factors. However, aside from a slightly poorer baseline memory performance, no significant associations were observed between HI and rates of domain-specific cognitive change over a 7-year follow-up period. These findings suggested that HI may serve as a potential risk factor for dementia in older adults, emphasizing the importance of further research.

In addition, research exploring different frequencies of hearing loss has also been conducted, such as the Mukari et al. (2017) study that investigated the association between hearing levels and cognitive function in older adults, particularly focusing on whether high-frequency hearing loss correlates with cognitive status. Involving 307 adults aged 60 years and older, the study assessed hearing using pure tone audiometry and cognitive function using the Mini Mental State Examination (MMSE). Results showed that while there was a significant but minimal relationship between low-

frequency hearing loss and general cognitive status, no such association was found with high-frequency hearing loss.

To consolidate all these research findings, a systematic review by Thomson et al. (2017) aimed to assess the evidence regarding hearing loss as a risk factor for dementia. Studies consistently indicated an association between hearing loss and dementia or cognitive decline in older adults. The review highlighted substantial methodological heterogeneity across the included studies, with varying definitions and assessments of both hearing loss and dementia. The reliance on peripheral auditory function assessments, such as pure tone audiometry, overlooked the potential contributions of central auditory dysfunction to cognitive decline. Similarly, the frequent use of tools like the MMSE for dementia diagnosis, while practical, lacked the sensitivity to detect subtle or early cognitive impairments. The underrepresentation of confounding factors like family history of dementia further limits the ability to isolate the independent impact of hearing loss. Despite methodological differences, the studies collectively supported the conclusion that hearing loss is linked to a higher incidence of dementia in older adults.

Additional studies have been conducted to investigate further and reinforce the connection between hearing loss and cognitive decline across various populations. Diao et al. (2019) examined the correlation between age-related hearing loss and cognitive impairment among elderly patients. A total of 201 elderly individuals admitted to the Department of Otorhinolaryngology of Peking University People's Hospital were evaluated using hearing screening and the Montreal Cognitive Assessment Scale. Through single-factor analysis and multivariate linear regression analysis, the study examined various factors affecting cognitive levels, including age, sex, education,

occupation, marital status, residence, average hearing loss, and duration of conscious hearing loss. Results indicated that the average degree of hearing loss significantly influenced cognitive impairment, particularly affecting directional force and abstract ability within cognitive domains. Additionally, factors such as age, self-reported hearing loss, years of education, marital status, past ear diseases, and hypertension were independent contributors to cognitive level. The study concluded that age-related hearing loss represents a risk factor for cognitive impairment among the elderly, particularly impacting abstraction and orientation.

Although studies established the presence of an association between hearing loss and cognitive decline, the question of whether this relationship is universally observed across all populations remained unresolved. The study by Cutler & Ilinca (2020) provided compelling evidence for a consistent global association between hearing acuity and cognitive difficulties across diverse populations, including data from 51 nations. Leveraging data from the Integrated Public Use Microdata International Series at the University of Minnesota, bivariate relationships between hearing and cognitive problems were analyzed using correlation coefficients (Rs), and multivariate relationships were explored using linear regression techniques (betas). The analysis controlled for demographic variables such as age, gender, marital status, and education. Results indicated a significant positive correlation between hearing problems and cognitive problems across all 51 countries, with an R-value of 0.334 ($p < .001$) and a multivariate beta of 0.316 ($p < .001$). Regional analyses also revealed statistically significant associations, suggesting that the link between hearing and cognition is consistent globally.

Other populations, such as individuals with mild cognitive impairment (MCI) and dementia, were examined to explore if this association persists. The systematic review and meta-analysis by Lau et al. (2022) provided strong evidence of an association between hearing loss and mild cognitive impairment (MCI). A total of 34 studies involving 48,017 participants were included, comprising prospective, cohort, cross-sectional, and observational studies. The findings revealed that 23 studies reported a significant association between hearing loss and MCI. The pooled risk ratio across all studies indicated a prevalence of MCI 1.44 times higher in individuals with hearing loss than those without. Furthermore, the analysis demonstrated a higher prevalence of peripheral hearing loss among individuals with MCI. When considering incidence, individuals with peripheral hearing loss were over twice as likely to develop MCI compared to those without hearing loss. However, a notable level of statistical heterogeneity was observed in the incidence analysis. Overall, the results stressed a substantial association between hearing loss and MCI, suggesting a potential link between these two conditions.

Another systematic review by Fu et al. (2022) demonstrated a significant association between hearing loss and cognitive impairment, including dementia, in older adults who speak a Sinitic tonal language. Twenty-nine unique studies comprising approximately 372,154 participants were included in the meta-analyses. The results revealed a significant negative effect size of cognitive function with hearing loss, indicating a correlation between the two variables. Both cross-sectional and cohort studies demonstrated a significant association between hearing loss, cognitive impairment, and dementia, with odds ratios of 1.85 and 1.89, respectively.

Paiva et al. (2023) conducted a cross-sectional, population-based cohort study in Florianópolis, Santa Catarina State, Southern Brazil, to investigate the association between self-reported hearing loss and cognitive impairment in older adults. Data were collected as part of the third wave of the EpiFloripa Aging study, which commenced in 2009 and continued until 2019. Cognitive impairment was assessed using the Mini-Mental State Examination (MMSE), while self-reported hearing loss, introduced in the last wave of the cohort, served as the primary exposure variable. Logistic regression analyses were employed, accounting for the study design and sample weights. Among 1,335 older adults evaluated, cognitive impairment was prevalent in 20.5% of cases, while 10.7% reported hearing loss. The study found that older adults with hearing loss were 2.66 times more likely to experience cognitive impairment compared to those without hearing loss, indicating a significant association between the two conditions.

The most recent study in this area investigated the longitudinal association between prevalent and incident HL and cognitive change in a cohort of 1823 participants aged 24 to 82 years from the Maastricht Aging Study (MAAS) (Soons et al., 2024). Assessments were conducted at baseline, 6, and 12 years, incorporating pure-tone audiometry. Linear-mixed models revealed that both prevalent and incident HL were associated with an accelerated decline in verbal memory, information processing speed, and executive function compared to participants without HL. Notably, the decline was consistent over time for prevalent HL but exhibited a time-delayed pattern from 6 to 12 years for incident HL. Importantly, the onset of HL preceded the onset of cognitive decline, highlighting HL as a potential risk factor independent of other dementia risk factors. Overall, these findings underscored the significance of addressing HL as a potential modifiable risk factor for cognitive decline and

emphasized the need for early intervention strategies to mitigate cognitive impairment associated with hearing loss.

2.1 Hearing Loss and Cognitive Function in Midlife Adults

A population-based cohort study investigated the association between hearing loss (HL) and incident dementia in Taiwanese adults by Liu & Lee (2019). Data from the National Health Insurance Research Database of Taiwan were utilized, with 8,135 patients newly diagnosed with HL from 2000 to 2011 constituting the exposed group, matched to individuals without HL (non-HL group). Over the follow-up period until 2013, of the total 16,270 participants, 1,868 developed dementia. The incidence rate of dementia was higher in the HL group compared to the non-HL group. After adjusting for various factors, patients with HL were found to have a significant risk of dementia. Subgroup analysis revealed that individuals aged 45 to 64 years with HL had a particularly elevated risk of dementia. These findings suggest that strategies such as hearing protection, screening, and treatment may be important for mitigating the potential risk of dementia associated with HL, especially in middle-aged adults. Further studies have been conducted to strengthen and expand the understanding of the relationship between hearing loss and cognitive decline; however, they predominantly focus on older adults, leaving the midlife population largely unexplored.

2.2 Neuroanatomical evidence

While studies have demonstrated a link between hearing loss (HL) and cognitive decline, the underlying mechanisms driving this association remain uncertain. For example, a systematic review and meta-analysis were conducted, synthesizing data from 40 studies across 12 countries (Loughrey et al., 2018). A total of 36 studies involving approximately 20,264 participants were included. The meta-analysis revealed

a small but significant association between age-related hearing loss (ARHL) and various domains of cognitive function. Cross-sectional studies indicated a significant association with cognitive impairment and dementia, while prospective cohort studies also showed associations, though not with Alzheimer's disease specifically. The lack of a consistent association with Alzheimer's disease specifically suggests that the mechanisms linking ARHL and cognitive decline may differ across dementia subtypes, yet these mechanisms remain underexplored.

Consequently, the review by Ralli et al. (2019) explored the relationship between hearing loss and Alzheimer's Disease (AD), presenting various hypotheses and potential implications for clinical practice. One prevailing theory posited that peripheral hearing deprivation may induce social isolation, thereby potentially predisposing individuals to dementia. Another hypothesis suggested that hearing loss may affect cortical processing, leading to a reallocation of cognitive resources towards auditory processing at the expense of other cognitive functions. Alternatively, changes in brain structure due to reduced peripheral auditory stimulation or a common underlying cause contributing to both conditions have also been proposed. However, the exact process remains unclear. To investigate this, several neuroanatomical studies have been conducted to examine brain changes associated with hearing loss.

In a cross-sectional study by Xu et al. (2019), the alterations in the thalamus and its subdivisions were investigated in individuals with sensorineural hearing loss (SNHL) compared to well-matched controls. Thirty-seven bilateral long-term SNHL patients and 38 controls underwent imaging assessments using T1-weighted imaging and arterial spin labeling (ASL) at 3 Tesla field strength. The study evaluated structural, functional, and perfusion changes in the thalamus, including relative volume, fractional

amplitude of low-frequency fluctuation (fALFF), and whole-brain functional connectivity. While no significant differences were found in the relative volume and perfusion of thalamic subdivisions, SNHL patients exhibited decreased fALFF, indicating reduced thalamic activity. Moreover, SNHL was associated with weakened thalamic connectivity with various brain regions, including the cerebellum, cingulate cortex, insula, and temporal gyrus. These functional connectivity abnormalities correlated positively with cognitive test scores and demonstrated high discriminative power between SNHL patients and controls. Overall, the findings suggested that SNHL induces widespread alterations in thalamic function and connectivity, potentially contributing to cognitive impairments associated with hearing loss.

Another study by Wang et al. (2022) conducted a comprehensive investigation across multiple datasets, including the UK Biobank, the Chinese Alzheimer's Biomarker and Lifestyle (CABLE) study, and the Alzheimer's Disease Neuroimaging Initiative (ADNI) database. Analyses revealed significant associations between poor hearing performance and cognitive decline in both the UK Biobank and the CABLE study. Moreover, hearing impairment was linked to reduced volumes of key brain regions and compromised white matter integrity. Additionally, individuals with a higher polygenic risk score for hearing impairment exhibited lower cognitive function, diminished grey matter volume, and impaired white matter tracts. Furthermore, hearing impairment was correlated with elevated cerebrospinal fluid levels and tau protein, a marker of neurodegeneration. Poor hearing performance was significantly linked to reduced volumes in the superior, middle, and inferior temporal gyri, hippocampus, precuneus, inferior parietal lobe, supramarginal gyrus, fusiform, and orbitofrontal cortex bilaterally, as well as in the left transverse temporal gyrus, left rostral anterior cingulate, and right rostral middle frontal gyrus. Similarly, lower volumes in the

amygdala, thalamus, and nucleus accumbens bilaterally were also significantly associated with poor hearing performance. Mediation analyses suggested that brain atrophy and tau pathology partially mediated the relationship between hearing impairment and cognitive decline. These findings highlighted the intricate interplay between hearing impairment, cognitive function, and neurodegenerative processes, underscoring the potential role of hearing impairment as a predictor of cognitive decline and dementia.

Meanwhile, a cross-sectional study investigated the impact of hearing loss on cognitive function in individuals with subjective cognitive decline (SCD), a condition characterized by self-reported cognitive decline without objective impairment on neuropsychological tests (Park et al., 2022). Participants aged 60 years and older were grouped into normal-hearing (NH) and bilateral HL groups based on audiometric assessments. Demographic, clinical, and cognitive measures, as well as brain volumes from MRI, were compared between the groups. Results revealed that individuals with HL performed worse on the Stroop Color Word Test, indicating deficits in frontal executive function, compared to those with NH. Additionally, HL was associated with reduced grey matter volumes in specific brain subregions including left temporal pole, left caudal middle frontal gyrus, left hippocampus, and right isthmus of the cingulate gyrus.

2.3 Impact of Hearing Loss on Cognition, Health and Well-Being

One recent study highlighted that hearing loss's effects extend beyond cognitive decline, influencing overall health and well-being (Mamo et al., 2023). In this study, the researchers investigated the interrelationships between hearing loss, cognitive status, and various health outcomes over a 2-year period in a sample of older adults

enrolled in the Program of All-Inclusive Care for the Elderly (PACE). The sample comprised 144 individuals, representing a diverse demographic range. Using medical chart data, respondents' cognitive and health statuses, including chronic conditions and hospital utilization, were assessed, while hearing status was measured at the beginning of the review period. Employing logistic regression and negative binomial hurdle models, the data was analyzed, and latent class analysis (LCA) was utilized to explore the potential clustering of respondents into distinct "health profiles" based on hearing, cognitive status, and health conditions. Findings revealed weak associations between hearing loss, heart disease, and diabetes, while cerebrovascular disease and falls were more strongly linked to both hearing loss and cognitive impairment. This indicated that hearing loss not only impairs cognitive function but also affects other health-related conditions.

Other aspects of health, along with the relationship between hearing loss and cognition, have also been explored. The study by Kawamura et al. (2023) aimed to investigate the impact of the interaction between hearing impairment and frailty on cognitive decline in community-dwelling older individuals. A mail survey was conducted among older adults aged 65 years and above who lived independently. Cognitive decline was determined using a self-administered dementia checklist, with a score of 18 or higher out of 40 indicating cognitive decline. Hearing impairment was assessed using a validated self-rated questionnaire, while frailty was evaluated using the Kihon checklist, categorizing participants into robust, pre-frailty, and frailty groups. Multivariate logistic regression analysis, adjusted for potential confounders, was conducted to assess the association of the interaction between hearing impairment and frailty with cognitive decline. The analysis included data from 464 participants. Results indicated that hearing impairment was independently associated with cognitive decline.

Furthermore, the interaction of hearing impairment and frailty significantly correlated with cognitive decline. Among participants in the robust group, hearing impairment was not linked to cognitive decline. Conversely, among those in the pre-frailty or frailty groups, hearing impairment was associated with cognitive decline. These findings suggested that the association between hearing impairment and cognitive decline is influenced by frailty status among community-dwelling older adults.

The longitudinal study by Ghisletta et al. (2023) elucidated the interconnected trajectories of sensorineural hearing loss, cognitive decline, and metabolic risk over time, highlighting their mutual influence in healthy adults. Utilizing latent change score models, data were collected from 687 relatively healthy adults aged 18.17 to 83.25 years over a span of more than 7 years. The findings revealed that changes in auditory and cognitive functioning over time were interrelated, with levels of functioning at one-time point influencing subsequent changes in both domains. Moreover, the study demonstrated that metabolic risk also played a role in influencing auditory and cognitive trajectories. These results suggested that auditory and cognitive functioning not only decline in parallel but also mutually influence each other's trajectories over time.

2.4 Contradicting studies

While studies consistently supported the association between hearing loss and cognition, other findings also emerged that contradicted this relationship. Croll et al. (2021) studied the relationship between hearing loss and cognitive decline study involving 3,590 non-demented participants. At baseline, hearing loss was associated with lower cognitive function, and over a follow-up period of approximately 4.4 years, it was linked to an accelerated decline in memory test performance. However, upon

further adjustment for the interaction between age and follow-up time, the association between hearing loss and accelerated cognitive decline became non-significant. This suggested that the effects of hearing loss on cognitive decline may not extend beyond the natural age-related declines in cognitive function.

Further, Irace et al. (2022) investigated the association between subclinical hearing loss and cognitive decline among cognitively normal adults aged 50 years and older using data from the Baltimore Longitudinal Study of Aging. Participants with pure-tone average ≤25 dB were included, and cognitive assessments were conducted between 1991 and 2019. Multivariable linear-mixed effects models were employed to analyze the relationship between hearing loss and changes in cognition over time while adjusting for various demographic and clinical factors. Results revealed that a 10-dB increase in hearing loss was associated with an annual decline in Letter Fluency test scores. However, no significant association was found between hearing loss and incident mild cognitive impairment or dementia.

Another group of researchers investigated the impact of self-reported hearing loss on longitudinal cognitive function in a cohort of late middle-aged adults without clinical impairment drawn from the Wisconsin Registry for Alzheimer's Prevention (WRAP) (Fields et al., 2020). A total of 579 participants were included, with hearing status determined by self-reported history of diagnosed hearing loss. Participants with self-reported hearing loss were matched with those without hearing loss based on age and sex. Linear mixed-effects models were employed to analyze associations between self-reported hearing loss and age-related cognitive trajectories, adjusting for covariates. Cognitive outcomes included speed and flexibility, visuospatial memory, and verbal fluency. Results showed that participants with self-reported hearing loss

performed significantly poorer on speed and flexibility measures compared to those without hearing loss, with no significant association observed for visuospatial memory or verbal fluency. Longitudinally, self-reported hearing loss was linked to a less rapid decline in speed and flexibility, but no difference was observed in the rate of decline for other cognitive measures. These findings challenged previous assertions regarding the association between self-reported hearing loss and accelerated cognitive decline.

Although there are some contradictory findings regarding the relationship between hearing loss and cognitive decline, these findings are relatively minimal and do not significantly challenge the overall evidence supporting the association. Most studies consistently demonstrate a link, suggesting that the contradictory results may arise from methodological differences, variations in sample populations, or other confounding factors.

2.5 Cognitive Flexibility and Inhibitory Control in Individuals with Hearing Loss

Huber et al. (2020) investigated the cognitive performance of older adults aged 60–80 years with severe to profound sensorineural hearing loss (SNHL) compared to a control group of peers with normal, age-adjusted hearing. The researchers employed a prospective matched case-control design with 30 participants in each group. The cognitive assessment battery included various tests targeting multiple domains: global cognition was assessed using the Mini-Mental Status Examination (MMSE) and the Clock Drawing Test (CDT); episodic memory was evaluated through the Word List tasks (measuring immediate and delayed recall) and Constructional Praxis and Recall; and executive functions, such as cognitive flexibility, attention, and inhibition, were measured using the Trail Making Test (TMT A and B) and the Stroop Test. The results revealed significant differences between the two groups. Participants with SNHL

showed poorer performance in the CDT, Word List tasks, TMT B, and the Stroop Test. These impairments were particularly notable in tasks involving verbal material and cognitive flexibility. Interestingly, the group differences in TMT B performance were mediated by the severity of depressive symptoms, highlighting the role of mood disorders in cognitive outcomes. No significant differences were found in non-verbal tasks, such as Constructional Praxis, or in simpler attention and processing speed tasks like TMT A. Furthermore, the higher prevalence of depressive symptoms in the hearing-impaired group appears to exacerbate deficits in cognitive flexibility.

Another study examined the relationship between hearing loss and cognitive functions in elderly individuals aged 60–65 years (Somnath et al., 2020). A cross-sectional study was conducted on 12 elderly mild to moderate hearing-impaired (EHI) individuals and 20 elderly normal-hearing (ENH) individuals. Audiological tests included pure-tone audiometry and speech audiometry, while cognitive assessments focused on mental speed of processing and working memory. Mental speed was evaluated using the Digit Symbol Substitution Test (DSST), a non-verbal test assessing visuomotor coordination, executive function, and mental processing speed. Working memory was assessed with verbal and visual N-back tasks, which included verbal N-back 1 and 2 and visual N-back 1 and 2, measuring working memory performance and complexity handling. Results indicated that EHI individuals performed significantly worse in mental processing speed and visual working memory, with larger differences observed in more complex tasks. Verbal working memory differences were less pronounced, attributed to task simplicity.

A significant study exclusively investigated cognitive flexibility and inhibition in older adults aged 60–85 years with mild age-related hearing loss (ARHL) compared

to age- and education-matched individuals with normal hearing (NH) (Shende et al., 2021). Cognitive flexibility was measured using the Trail Making Test-B (TMT-B), Verbal Fluency tasks (Category and Letter Fluency), and the Stroop test's interference/switching condition. Inhibition was assessed through the Stroop interference condition, and two Go/NoGo tasks: Single-Car (simpler categorization) and Object-Animal (more complex categorization). Participants included 21 older adults with ARHL and 18 NH controls, all assessed for peripheral hearing using pure-tone audiometry (PTA) and central hearing via the Quick Speech-in-Noise test (QuickSIN). Results revealed that individuals with ARHL performed worse on inhibitory tasks, as evidenced by longer Stroop task completion times and higher error rates on NoGo trials in both Go/NoGo tasks. However, no significant differences were found in measures of cognitive flexibility. Significant correlations emerged between hearing ability and cognitive performance: poorer peripheral hearing (PTA) and central hearing (QuickSIN) were linked to reduced inhibition and cognitive flexibility, particularly in more complex tasks. These findings suggest that even mild ARHL is associated with specific cognitive control deficits, highlighting the need for comprehensive audiological and cognitive assessments in this population.

To summarize, a narrative review by Shende & Mudar (2023) provides an in-depth synthesis of existing research on the interplay between age-related hearing loss (ARHL) and cognitive control processes, focusing on cognitive flexibility and inhibitory control. Cognitive flexibility, a set of executive functions that regulate behavior to achieve goals, is increasingly recognized as being impacted by ARHL. The review categorises findings based on specific cognitive processes, highlighting their assessment methods and the associated outcomes in older adults with varying levels of ARHL.

The evidence consistently suggests that ARHL is associated with declines in cognitive flexibility, particularly in long-term follow-ups. For example, studies have found that individuals with greater hearing loss take longer to complete tasks requiring mental set-shifting, such as TMT-B. Similarly, lower DSST scores, which measure the ability to switch between digit-symbol pairings, are frequently associated with poorer hearing thresholds. Longitudinal studies highlight a dose-response relationship, where greater severity of hearing loss corresponds to larger declines in flexibility over time. However, some cross-sectional studies reported no significant associations, potentially due to differences in hearing aid usage, age ranges, or methodological designs.

The inhibitory control component, which allows suppression of irrelevant information or responses, is often evaluated using the Stroop Task and Go/NoGo paradigms. The Stroop Task's interference condition, requiring participants to suppress habitual responses (e.g., reading words instead of naming ink colors), has revealed that individuals with ARHL show slower response times and higher error rates, indicating impaired inhibition. Go/NoGo tasks, which assess the ability to withhold responses in specific conditions, similarly show reduced performance in ARHL populations. While some studies reported robust associations between hearing loss and inhibitory control deficits, others found no significant differences, particularly in samples that included hearing aid users, suggesting a potential mitigating effect of amplification on cognitive control. The review emphasises that alterations in cognitive control processes associated with ARHL are likely due to a combination of sensory and central processing deficits. These deficits may stem from increased cognitive load due to auditory processing difficulties, which can reduce cognitive resources available for executive functions.

In summary, the existing literature demonstrates a strong connection between hearing loss and cognitive decline, with most research focusing on older adults and limited attention given to midlife individuals. There have been no studies explicitly targeting early identification, such as during midlife or at the onset of cognitive decline associated with mild hearing loss. Additionally, promising cognitive processes like cognitive flexibility and inhibitory control remain underexplored to understand this association early.

Chapter 3

Methods

The present study aimed at investigating the cognitive flexibility and inhibitory control in adults with hearing loss using different outcome measures like accuracy in verbal fluency tasks, completion time in Trail making test-B (TMT-B) (Reitan, 1958), accuracy and reaction time in Stroop task (Stroop, 1935) and Go/NoGo tasks (Gordon & Caramazza, 1982). The particulars of the method in the present study are discussed below.

3.1 Study design

A standard group comparison was used to compare the performance between adults with and without hearing loss. Adults with hearing loss formed the clinical group and adults without hearing loss formed the normal group.

3.1.1 Sample size and sampling

The sample size was calculated using G*power software (version 3.1.9.6) (Erdfelder et al., 2009) utilizing the mean and standard deviation obtained from the pilot study. To determine the necessary sample size for comparing two independent groups, t-tests were selected as the test family, and the statistical test, Means: Difference between two independent means (two groups) was chosen. For the type of power analysis, Apriori: Compute required sample size – given α, power, and effect size was selected to calculate the required sample size based on specified parameters. An effect size (Cohen's d) of 0.5, the significance level (α) of 0.05, power of the test (1- β) at 0.80 and allocation ratio of 1 was used. The analysis prescribed a sample size ranging from 5 to 10. Participants in the pilot study were not included in the main study

to avoid bias and ensure the validity of the results. A purposive sampling method was employed to collect samples for the present study.

3.2 Participants

A total of forty adults were recruited for the study consisting of nineteen adults with hearing loss (10 females, 9 males; mean age: 50.44 ± 2.84 years) formed the 'clinical group' (AHL group) and twenty-one neurotypical adults with normal hearing sensitivity (11 females, 10 males; mean age: 49 ± 3.29 years) constituted the 'normal group' (NTA group). The age of the participants ranged between 45 to 55 years.

3.2.1 Exclusionary criteria

Individuals with a history of communication disorders, learning disabilities, neurological disorders, traumatic brain injury, or psychiatric disorders, substance abuse, use of psychoactive medications, congenital hearing loss, known causes of hearing loss such as noise exposure, injuries, ototoxicity, unilateral or bilateral continuous tinnitus, those using hearing aids and experiencing significant vision issues such as untreated cataracts, macular degeneration, glaucoma, and retinopathy were excluded.

3.2.2 Common inclusionary criteria

All participants were right-handed, native Kannada speakers, and urban community dwellers with normal or corrected vision. All participants demonstrated good proficiency level in English according to the adapted version of Language Experience and Proficiency Questionnaire (LEAP-Q) for the Indian context (Maitreyee & Goswami, 2009). All the participants had more than 12 years of formal education and obtained a total score of >11 in the Modified Kuppuswamy socioeconomic scale

2023 (Radhakrishnan & Nagaraja, 2023) indicating that the participants belonged to middle class and above. Additionally the participants scored above 26 on the Montreal Cognitive Assessment in Kannada (MoCA) (Kaul et al., 2022), ensuring the absence of potential cognitive impairment.

3.2.3 Group specific inclusionary criteria

All participants underwent the following routine/preliminary tests by an audiologist before the commencement of the experimental procedures to ensure the group specific inclusionary criteria were met;

- A detailed history was collected from all participants to rule out any otological, neurological, neuropsychiatric, and/or speech-language delays/disorders.

- Air conduction (AC) and bone conduction (BC) pure-tone thresholds were assessed in both ears using the modified Hughson-Westlake procedure (Carhart & Jerger, 1959). Thresholds were recorded for octave frequencies ranging from 250 Hz to 8000 Hz for AC and 250 Hz to 4000 Hz for BC, respectively.

- Speech identification scores in quiet were determined using standard phonemically balanced word lists in the Kannada language (Yathiraj & Vijayalakshmi, 2005) developed at the All India Institute of Speech and Hearing. All participants achieved speech identification scores exceeding 90% in quiet conditions.

- Tympanograms were measured in all participants for a 226 Hz probe-tone. Additionally, ipsilateral and contralateral acoustic reflex thresholds were measured for the frequencies of 500 Hz and 1000 Hz. All participants were

ensured of having normal middle ear functioning in both ears as indicated by an 'A' type tympanogram along with normal ipsilateral and contralateral acoustic reflex thresholds at 500 Hz and 1000 Hz.

- The hearing sensitivity of the normal group was within ≤15 dB HL at frequencies 250 Hz to 8000 Hz for AC and 250 Hz to 4000 Hz for BC. The hearing sensitivity of the clinical group was between 25 dB HL to 40 dB HL (Clark, 1981) for similar frequencies for both AC and BC. Hence, the clinical group consisted of adults diagnosed with bilateral mild sensorineural hearing loss and the normal group consisted of adults with bilateral normal hearing sensitivity.

- The mean hearing thresholds for both groups for the right and left ear are presented in Table 3.1.

- The demographic details and additional data regarding the presence or absence of comorbid conditions such as hypertension and diabetes, as well as lifestyle habits including alcohol consumption, smoking, and exercise, were collected and presented in Table 3.2.

Table 3.1

Mean hearing thresholds for the participants in AHL and NTA groups

	AHL				NTA			
	Right ear		Left ear		Right ear		Left ear	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
500 Hz	26.80	4.87	24.60	4.98	6.00	3.53	5.80	3.73
1000 Hz	29.80	4.12	28.60	6.21	8.60	3.06	9.20	3.73
2000 Hz	32.80	4.26	32.80	5.01	10.80	3.73	11.00	3.53
4000 Hz	37.20	3.84	39.40	6.00	14.80	3.37	15.00	3.22
PTA	31.65	3.28	31.35	4.47	10.05	2.51	10.25	2.36
SRT	34.40	6.00	33.80	6.96	14.20	4.25	14.20	4.25
SIS	94.72	2.76	95.84	3.36	100.00	0.00	100.00	0.00

Note. AHL = Adults with Hearing Loss; NTA = Neurotypical Adults; SD = Standard Deviation; Hz = Hertz; PTA = Pure Tone Average; SRT = Speech Recognition Threshold; SIS = Speech Identification Score

Table 3.2

Demographic details of the participants

Sl No	Age	Sex	Education	Occupation	SES	L1	Other languages known	Hypertension	Diabetes	Alcohol Consumption	Smoking	Physical Exercise	PTA - R	PTA- L	PD
1	45	F	Professional degree	Lecturer	II	K	E, Mal	No	No	No	No	No	5	5	BNHS
2	46	M	Graduate	Engineer	I	K	E, H, Ma	Yes	No	No	No	Yes	7.5	8.75	BNHS
3	45	F	Graduate	Manager	II	K	E, H, Ma	No	No	No	No	No	8.75	10	BNHS
4	49	F	Graduate	Home maker	II	K	E, Ta	Yes	Yes	No	No	Yes	6.25	7.5	BNHS
5	48	F	Graduate	Nurse	II	K	E, Ta	No	No	Yes	No	No	11.25	11.25	BNHS
6	45	M	Professional degree	Doctor	II	K	E	Yes	No	No	No	Yes	7.5	7.5	BNHS
7	46	M	Professional degree	Professor	II	K	E, H	No	No	No	No	No	10	10	BNHS
8	53	M	Professional degree	Professor	II	K	E	No	No	No	Yes	No	12.5	12.5	BNHS
9	54	F	Professional degree	Doctor	II	K	E, H	Yes	No	No	No	Yes	8.75	10	BNHS
10	55	F	Professional degree	Doctor	II	K	E, H, Te	No	No	No	No	No	12.5	12.5	BNHS
11	55	F	Diploma	Technician	II	K	E	No	Yes	No	No	Yes	10	10	BNHS
12	45	F	Professional degree	Doctor	II	K	E, H	No	No	No	No	No	13.75	13.75	BNHS
13	46	F	Graduate	Home maker	II	K	E, Mal	Yes	No	Yes	No	No	10	10	BNHS

14	47	M	Graduate	Technician	II	K	E, H, Tu	No	No	No	No	Yes	6.25	6.25	BNHS
15	48	M	Professional degree	Engineer	II	K	E, H	No	No	No	Yes	Yes	8.75	8.75	BNHS
16	49	M	Graduate	Bank employee	II	K	E	Yes	No	No	No	No	10	11.25	BNHS
17	49	F	Graduate	Bank employee	II	K	E	No	No	No	No	No	8.5	13.75	BNHS
18	49	F	Graduate	Home maker	II	K	E, C	Yes	No	No	No	Yes	13.75	12.5	BNHS
19	48	M	Professional degree	Lecturer	II	K	E, H	No	Yes	No	No	No	11.25	11.25	BNHS
20	51	M	Graduate	Teacher	II	K	E, Te, Ma	No	No	No	No	Yes	12.5	12.5	BNHS
21	49	M	Graduate	Counsellor	II	K	E, H, Ma	No	No	No	No	No	8.75	8.75	BNHS
22	50	F	Graduate	Home maker	II	K	E, H	Yes	No	Yes	No	Yes	31.25	28.75	BMSNHL
23	46	M	Graduate	Pharmacist	II	K	E, H, Ma	No	No	No	No	No	27.5	26.25	BMSNHL
24	51	F	Graduate	Lecturer	II	K	E	Yes	Yes	No	No	No	33.75	27.5	BMSNHL
25	46	F	Diploma	Technician	II	K	E, H, Te, Ta, Mal	No	No	No	No	Yes	28.75	28.75	BMSNHL
26	50	F	Graduate	Manager	II	K	E, C, Ta	Yes	No	Yes	No	Yes	35	28.75	BMSNHL
27	46	M	Professional degree	Engineer	II	K	E	Yes	Yes	No	No	No	31.25	26.25	BMSNHL
28	47	F	Graduate	Teacher	II	K	E, H	No	No	No	No	Yes	32.5	26.25	BMSNHL
29	53	F	Graduate	Home maker	II	K	E, Te	Yes	Yes	No	No	No	30	28.75	BMSNHL

30	49	F	Graduate	Home maker	II	K	E	No	Yes	No	Yes	No	31.25	33.75	BMSNHL
31	55	F	Professional degree	Head mistress	II	K	E, Ta, Te	No	No	No	No	No	27.5	30	BMSNHL
32	50	M	Graduate	Cashier	II	K	E	No	No	Yes	No	Yes	36.25	28.75	BMSNHL
33	49	M	Graduate	Driver	II	K	E	No	Yes	No	No	No	30	32.5	BMSNHL
34	53	M	Graduate	Constructor	II	K	E	No	No	No	No	Yes	27.5	33.75	BMSNHL
35	54	F	Professional degree	Professor	II	K	E	No	Yes	No	No	Yes	28.75	26.25	BMSNHL
36	53	F	Graduate	Home maker	II	K	E	No	No	No	No	Yes	26.25	37.5	BMSNHL
37	49	M	Graduate	Electrician	II	K	E, Ko	No	Yes	No	No	No	31.25	35	BMSNHL
38	55	F	Graduate	Home maker	II	K	E	No	No	No	No	Yes	33.75	36.25	BMSNHL
39	46	M	Graduate	Teacher	II	K	E	No	No	No	No	Yes	38.75	35	BMSNHL
40	48	M	Graduate	Police	II	K	E	No	No	No	No	No	37.5	37.5	BMSNHL

Note. SES = Socio Economic Scale; I = upper class; II = upper middle class; III = Lower middle class; L1 = Native language; K = Kannada; E = English; H = Hindi; Ta = Tamil; Te = Telugu; Ma = Marathi; Tu = Tulu; C = Coorgi; Ko = Konkani; Mal = Malayalam; F = Female; M = Male; PTA-R = Pure Tone Average in the Right ear; PTA-L = Pure Tone Average in the Left ear; PD = Provisional Diagnosis; BNHS = Bilateral Normal Hearing Sensitivity; BMSNHL = Bilateral Mild Sensorineural Hearing Loss

3.3 Test environment

All audiological assessments were carried out in acoustically-treated, electrically-shielded double room set-ups with noise levels within permissible limits (American National Standards Institute, 1999). The main experiments were carried out in quiet rooms with no distractions.

3.4 Instrumentation and software

The following instruments and software were used for the different experimental procedures and analyses, as well as for the routine/preliminary procedures;

- The pure tone audiometry was carried out using Inventis Piano, a two-channel diagnostic audiometer (Inventis, 35127 Padova, ITALY).
- The hearing thresholds for AC were obtained using TDH-50P supra-aural headphones (Telephonics, Farmingdale, NY, USA).
- The hearing thresholds for BC were obtained using a B71 bone vibrator (Radioear, Kimmetrics, Smithsburg, MD, USA).
- The immittance evaluations were performed using GSI- Tympstar Middle ear Analyzer (Grason Stadler Inc.-GSI-61; Milford, NH, USA).
- The Stroop and Go/NoGo tests were programmed and presented in PsyToolkit software (Stoet, 2010, 2017).
- MacBook Pro (Apple Inc, Cupertino, USA) laptop for stimulus presentation and response acquisition for the Stroop and Go/NoGo tasks.

3.5 Ethical consideration

The present study was approved by the Ethical Committee for bio-behavioral research involving human subjects at the All India Institute of Speech and Hearing (AIISH), Mysuru, India (Reference code: No.DOR.9.1/Ph.D/PC/930/2021-22, Appendix A). The participants were recruited for the study only after obtaining their written consent (Appendix B) as per the ethical guidelines for bio-behavioral research involving human subjects of the All India Institute of Speech and Hearing (Basavaraj & Venkatesan, 2009). All the participants and their caregivers were explained about the need, procedure, and approximate duration of the tasks. They were assured of safety during testing and confidentiality regarding their details.

3.6 Pilot study

The pilot study was conducted on ten adults with hearing loss and ten adults with normal hearing sensitivity who were not included in the main study. The purpose was to determine the stimuli, tasks, and presentation-related parameters for the main study. The findings of the pilot study confirmed the suitability of the majority of the parameters for use in the main study. Specifically:

- Stimulus-Related Parameters: The programming of the stimuli used was verified and deemed appropriate for both groups without requiring further modifications.
- Presentation-Related Parameters: The number of attempts allowed and the response duration provided were sufficient to ensure fair participation and understanding of the tasks by both groups.

- Task-Related Parameters: The mode of task presentation and the order of tasks were found to be well-structured and effective for participants in both groups.

However, one key adjustment was made based on the pilot study results: Stimulus Duration on the Stroop Task: Initially, the stimulus in the Stroop task was presented for 2000 milliseconds. Both groups performed poorly under this condition, suggesting that the duration was insufficient to process the task effectively. Consequently, the stimulus duration was increased to 5000 milliseconds for the main study to ensure better performance and comprehension.

3.7 Procedure

The study was conducted in two phases. Phase I- Pre-data collection and Phase II- Data collection and analyses.

3.7.1 Phase I- Pre-data collection

The study's pre-data collection phase involved the following steps.

Step 1: Obtaining informed consent

Since the study involved human subjects, it was ensured that participants understood the purpose of the study, what their involvement would entail, any potential risks or benefits, and their right to withdraw at any point without any consequences.

Step 2: Obtaining general information through self-report

After obtaining consent, participants were asked to provide general information through self-report. This included demographic data as well as any relevant medical history, particularly related to their hearing status such as onset and progression. The

hearing loss onset was gradual and remained stable for most of the participants in the clinical group.

Step 3: Cognition screening using MoCA

The MoCA was used to screen participants for cognitive function by the investigator of the present study. Only those participants who passed the cognitive screening by obtaining a score >26, were included in the study.

Step 4: ENT evaluation

Participants underwent an evaluation by an ENT specialist to identify any otological issues that could affect their hearing or auditory processing. This screening was important to rule out medical conditions, such as ear infections or structural abnormalities, which could influence hearing performance.

Step 5: Audiological assessments

After the ENT evaluation, participants underwent a series of audiological assessments including pure-tone audiometry, speech audiometry, and tympanometry. These audiological assessments provided a detailed profile of each participant's hearing capabilities, ensuring that the hearing loss group had documented hearing impairment and that the normal group had normal hearing sensitivity, which has been elaborated in the inclusionary criteria.

Step 6- Programming of stimuli

The next step involved selecting and programming stimuli for two tasks: the Stroop task and the Go/NoGo task. Both tasks were selected and programmed using PsyToolkit, a software tool for creating and running cognitive psychology experiments.

It was also used to precisely control stimulus presentation and acquire accurate responses during data collection, ensuring consistency in task administration.

3.7.2 Phase II- Data collection and analyses

This phase consisted of data collection that included the assessment of cognitive flexibility and inhibitory control tasks, which was conducted using four tasks. Participants were seated comfortably in a chair within a well-lit room, free from noise and distractions, to ensure optimal conditions for data collection. Instructions were provided in Kannada or English based on the participants' convenience. The verbal fluency tests and TMT-B were utilized to assess cognitive flexibility, while the Stroop and Go/NoGo tasks were employed to evaluate inhibitory control. The following tasks were carried out in the same order which are described in detail below.

- Verbal fluency tests
- Trail-making test B
- Stroop test
- Go/NoGo test

3.7.2.1 Verbal fluency tests

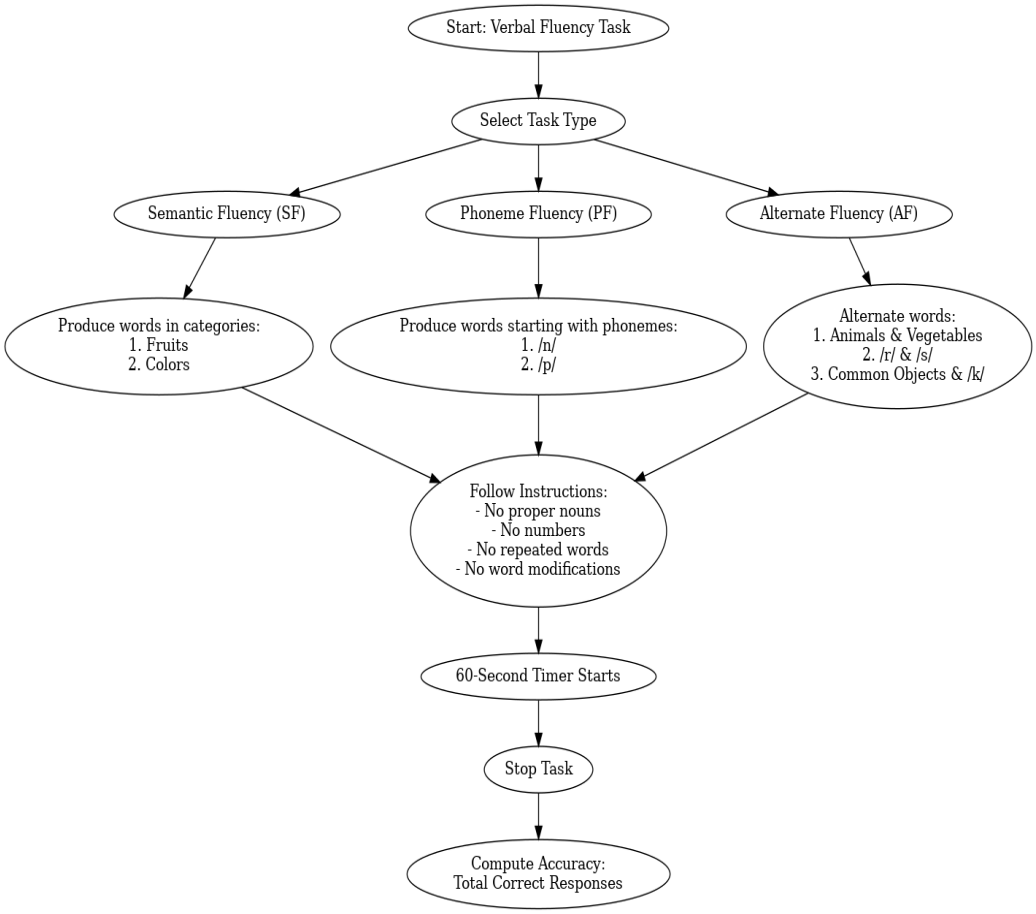
Each participant completed seven verbal fluency (VF) tasks in total, which comprised semantic fluency (SF), phoneme fluency (PF), and alternate fluency (AF) tasks, which required producing as many different words as possible within 60 seconds. Two tasks were provided for each semantic fluency and phoneme fluency and three tasks were provided to assess alternate fluency.

Instructions: In the semantic fluency task, the participants were asked to produce words in two semantic categories: fruits and colors. In the phoneme fluency task, the participants were asked to produce words beginning from two phonemes in Kannada: /n/ and /p/. In the alternate fluency task, the participants were instructed to alternate the words in three conditions. Task (1) alternate between two semantic categories: animals and vegetables, Task (2) alternate between two phonemes: /r/ and /s/, and Task (3) alternate between the semantic category of common objects and the phoneme /k/. The participants were instructed to perform the task without using proper nouns, numbers, reiterating previously named words or using the same word with a different prefix or suffix. Timing commenced as soon as participants were prompted to begin using a stopwatch. The stopwatch was pressed as quickly and accurately as possible. As soon as 60 seconds were completed the participants were instructed to stop the task. The total number of correct responses was computed as accuracy in the present study.

Scoring: The obtained responses were audio-recorded and analysed by the investigator. A score of 1 was allocated for each correct word response, while a score of 0 was assigned for every incorrect word response provided by the participants during the semantic and phonemic fluency tasks. For the alternate fluency task, a score of 1 was provided for a correct alternate pair of words. A score of 0 was assigned when the participant either provided an incorrect response or failed to alternate between the specified pair.

Figure 3.1

Process Flowchart for Verbal Fluency Tasks



3.7.2.2 Trail Making Test B

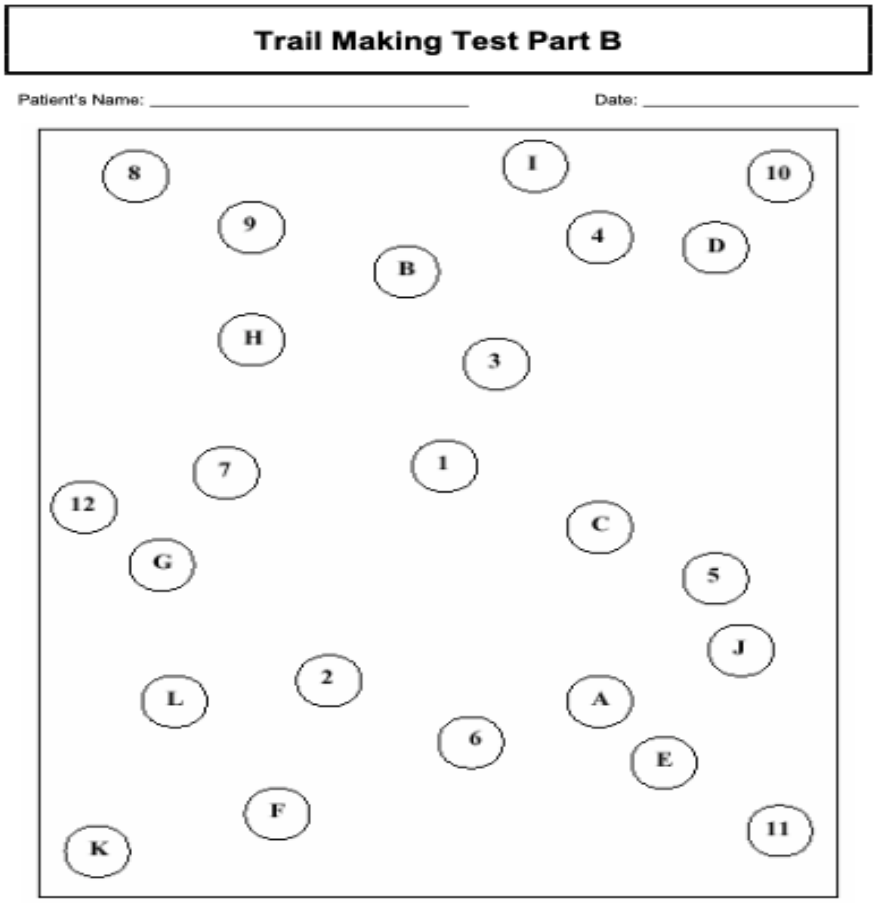
Instructions: Participants were instructed to sequentially connect encircled numbers and letters, alternating between the two sequences (e.g., 1-A-2-B, and so on) consecutively in a progressive manner, up to the number 13 as quickly and correctly as possible as shown in Figure 3.2. The encircled numbers were printed on paper and a pen was provided to connect them. Timing commenced as soon as participants were prompted to begin using a stopwatch. The stopwatch was pressed as quickly and accurately as possible as soon as the participant started and completed the test.

Whenever an error was made the examiner crossed out the erroneous line and provided immediate feedback. The test was discontinued if the participant failed to complete the test within 300 seconds. The test was administered following the protocol outlined by Bowie & Harvey (2006).

Scoring: The time taken to complete the task was noted in terms of milliseconds. The duration was calculated from the beginning of the task till the end of the task.

Figure 3.2

Stimulus for Trail Making Test-B



3.7.2.3 Stroop test

The Stroop test was selected and programmed in PsyToolkit and performed on a MacBook Pro laptop. Four colors and their names were included in the test namely red, green, blue, and yellow. Two types of stimuli included congruent and incongruent stimuli. There were two conditions in the Stroop task. For instance, condition 1 is the congruent condition where the word 'blue' is written in 'blue' color, and condition 2 is the incongruent condition where the word 'blue' is written in 'red' color as depicted in Figure 3.3. The congruent and incongruent conditions appeared randomly for all four colors. Participants were given a fixed interval to respond to each stimulus before the next one appeared. The stimulus and inter-stimulus duration were 5000 and 1000 milliseconds respectively. The same process was used for both test scenarios, where the congruent and incongruent conditions were displayed in random order. The participants were briefed about the test where different color names will appear on the screen with different colored inks. It was emphasized that the goal is to press the initial letter of the color of the ink, not the word itself.

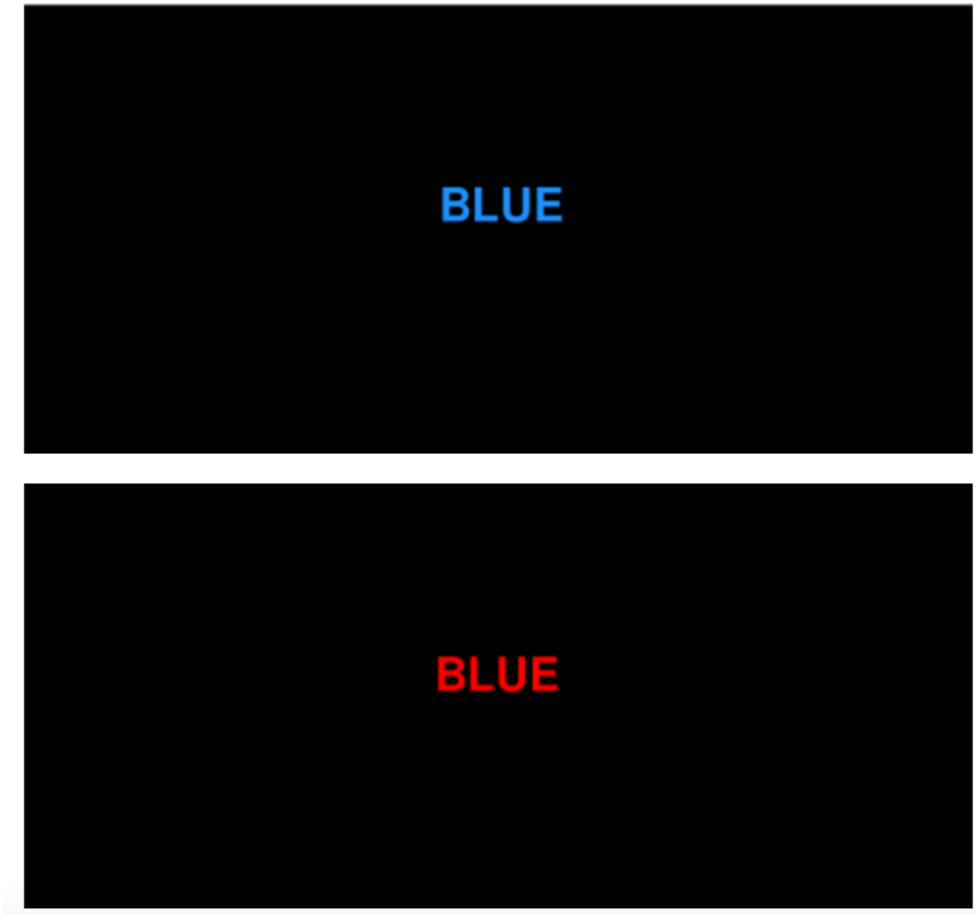
Instructions: The participants were instructed to shift their focus on the ink color and not the text, disregarding the written text. For example, if the word 'blue' appeared on the screen in 'blue' colored ink, the participant was expected to press the key 'B'. If the word 'blue' appeared on the screen in 'red' colored ink, the participant was expected to press the key 'R'. The instructions also appeared on the screen for the participants to read. The participants were provided with a response pad which was indigenously prepared and customized for the present study. The response pad consisted of only four keys that read Y, G, R, and B indicating the initial alphabets of colors used in the task namely, yellow, green, red, and blue respectively. A total of 45 trials were given per

participant including 5 practice trials, 20 congruent and 20 incongruent trials. The number of congruent and incongruent stimuli was equally divided for each participant. The reaction time (RT) and accuracy scores were automatically recorded on the software (Appendix C).

Scoring: A score of 1 was allotted for each correct response and a score of 0 for incorrect responses. A total of four outcome measures were collected at the end of the task that included accuracy, average RT, RT for congruent and incongruent conditions, and the difference between the two was computed as the Stroop effect by the investigator. RT was measured in milliseconds for all the outcome measures.

Figure 3.3

An Example of Stimulus for Stroop task for Congruent and Incongruent Conditions



3.7.2.4 Go/NoGo task

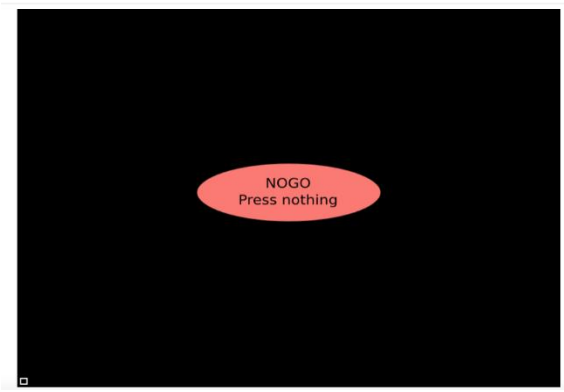
The Go/NoGo task was performed in PsyToolkit on a MacBook Pro laptop by the investigator. The Go stimulus appeared on the screen in green color and the NoGo stimulus appeared in red as depicted in Figure 3.4.

Instructions*:* Participants were instructed to press the space bar as fast as possible when the Go stimulus appeared on the screen and to inhibit or withhold their response when the NoGo stimulus emerged. Instructions also appeared on the screen along with the stimulus that read whether to press or not to press the key. A total of 30 trials were given per participant including 5 practice trials. The stimulus duration for Go and NoGo stimulus were 500 milliseconds and 2000 milliseconds respectively. The inter-stimulus duration was 500 milliseconds. The RT and accuracy scores were automatically recorded on the software.

Scoring: For every correct and incorrect response, a score of 1 and 0 was allotted respectively (Appendix D).

Figure 3.4

An Example of Stimulus for Go/NoGo task



For all the tasks, the participants were required to repeat the instructions before starting the test to ensure they understood the test instructions. If the participants were able to repeat the instructions appropriately, the examiner began the test. If they failed to do so, instructions were given to the participants again. The test commenced only after the participants repeated the test instructions correctly. This protocol adhered to the concern of participants with hearing loss as they took part in the study in an unaided condition, and the goal was to confirm that the reduction in hearing sensitivity did not impede their comprehension of the task instructions. All data gathered from the participants, including performance metrics from all the tasks were compiled, analyzed, and organized for further statistical analysis. A flowchart depicting a summary of the procedure is presented in Figure 3.5.

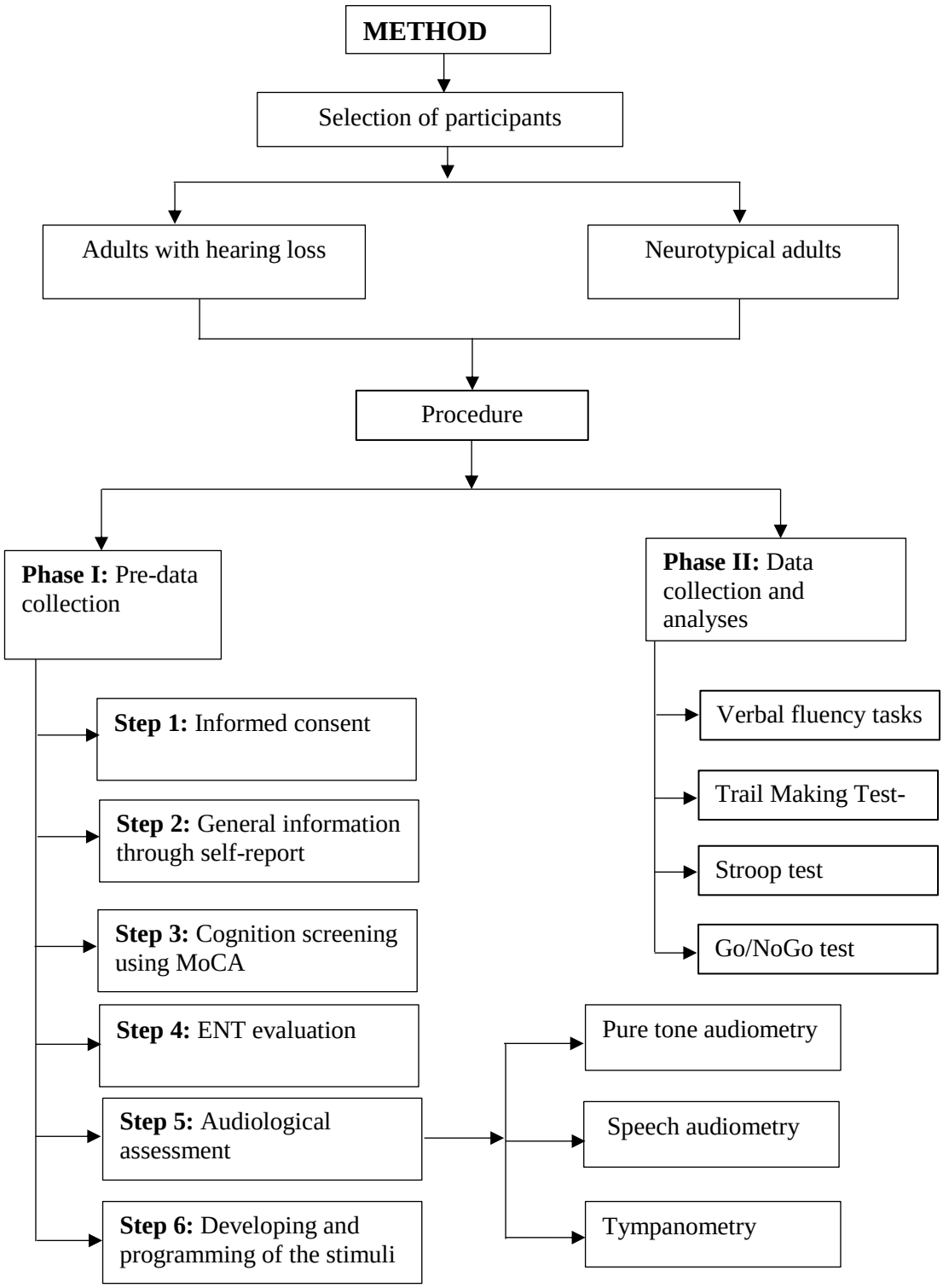
3.8 Statistical analysis

Statistical analyses were conducted using Statistical Package for Social Sciences version 26.0 (SPSS Inc, Chicago). Parametric tests were predominantly employed due to the normal distribution of the data, as indicated by the Shapiro-Wilk test of normality. In cases where the data deviated from normality, non-parametric tests were utilized. Descriptive statistics, including mean, median, standard deviation, and interquartile range, were calculated. Mann-Whitney U test was performed to assess differences in verbal fluency tasks between AHL and NTA groups. Independent sample t-tests were conducted to compare completion times of the TMT-B and RT in congruent and incongruent conditions of the Stroop task between AHL and NTA groups. Additionally, Mann-Whitney U tests examined differences in accuracy, RT, and Stroop effect of the Stroop task, while another independent sample t-test evaluated RT in the Go/NoGo task between AHL and NTA groups. Spearman's rank correlation coefficient

was used to assess the relationship between outcome measures, while the Chi-square test was employed to examine the association between groups and health & lifestyle related factors.

Figure 3.5

Flowchart Depicting a Summary of the Procedure in the Present Study



Chapter 4

Results

The present study aimed at investigating cognitive flexibility and inhibitory control in adults with hearing loss. The cognitive flexibility and inhibitory control were explored using four tasks that included verbal fluency tests, Trail Making Test-B (TMT-B), Stroop test, and Go/NoGo tasks. Accuracy was measured in verbal fluency tests, completion time was measured in TMT-B, and accuracy and reaction time were measured in both Stroop and Go/NoGo tasks. The performance of adults with hearing loss on these tasks was compared to the performance of adults with normal hearing.

The data obtained from 19 adults with hearing loss (AHL) and 21 neurotypical adults (NTA) who participated in the study were analyzed. Analyses of performance were done to meet the study objectives which were as follows:

1. To compare the performance on verbal fluency task in terms of accuracy between adults with hearing loss and neurotypical adults.

    a. To compare the performance on semantic fluency in terms of accuracy between adults with hearing loss and neurotypical adults.
    b. To compare the performance on phoneme fluency in terms of accuracy between adults with hearing loss and neurotypical adults.
    c. To compare the performance on alternate fluency in terms of accuracy between adults with hearing loss and neurotypical adults.

2. To compare the performance on Trail making test-B in terms of completion time between adults with hearing loss and neurotypical adults.

3. To compare the performance on the Stroop task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults.

    a. To compare the performance in terms of accuracy between adults with hearing loss and neurotypical adults.
    b. To compare the performance in terms of average reaction time between adults with hearing loss and neurotypical adults.
    c. To compare the performance in terms of reaction time in congruent and incongruent conditions between adults with hearing loss and neurotypical adults.
    d. To compare the performance of the Stroop effect between adults with hearing loss and neurotypical adults.

4. To compare the performance on the Go/NoGo task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults.

    a. To compare the performance on the Go/NoGo task in terms of accuracy between adults with hearing loss and neurotypical adults.
    b. To compare the performance on the Go/NoGo task in terms of reaction time between adults with hearing loss and neurotypical adults.

5. To study the relationship between outcome measures of Verbal fluency test, Trail making test B, Stroop task and Go/NoGo task.

6. To study the association between groups and health & lifestyle related factors.

Statistical tests were conducted to evaluate the objectives using Statistical Package for Social Sciences version 26.0 (SPSS Inc, Chicago). The following statistical tests were carried out to evaluate the objectives:

- Descriptive statistics were obtained including mean, median, standard deviation, interquartile range, and quartiles.
- Shapiro-Wilk test was used to check the normality of the data.
- Mann-Whitney U test was used to check for the statistical difference in the accuracy for all the verbal fluency tasks including semantic fluency, phoneme fluency, and alternate fluency between two groups (AHL and NTA).
- Independent sample t-test was used to determine the statistical difference in completion times of the TMT-B between the two groups (AHL and NTA).
- One-way MANOVA was used to check for the statistical difference in RT in congruent and incongruent conditions of the Stroop task between two groups (AHL and NTA).
- Mann-Whitney U test was used to check for the statistical difference in accuracy, average RT, and Stroop effect of the Stroop task between the two groups (AHL and NTA).
- Independent sample t-test was used to determine the statistical difference in RT of the Go/NoGo task between the two groups (AHL and NTA).
- Spearman's rank correlation coefficient was used to assess the correlation between outcome measures.
- Chi-square test was used to examine the association between groups and health & lifestyle related factors.
- The effect sizes for parametric analyses were determined using the formula for partial eta-squared (η_p^2). A η_p^2 value between 0.01 and <0.06 was considered as

small effect size, while a η_p^2 value of >0.06 and <0.14 was considered as medium effect size, and a η_p^2 value of >0.14 was considered as large effect size (Cohen, 2013).

- The effect sizes for the non-parametric analyses were computed using the formula, $r_e = |z|/\sqrt{N}$ (Rosenthal, 1991); where N is the total number of participants in the study. An effect size of 0.3 was considered low, 0.3 to 0.5 was considered as medium effect size, and any value greater than 0.5 was considered as high effect size (Field, 2013).

Reliability measures

The inter-rater and intra-rater reliability of dependent variables (accuracy measures for verbal fluency tasks) was measured by analyzing the audio-recorded samples for 20% (8 samples) of the data.

Inter-rater reliability*:* To assess inter-rater reliability, 20% of the randomly selected participant responses were given to a speech-language pathologist familiar with the test used in the study. The rater was explained all the operational definitions laid for this study and was given the training to analyze the samples before the data analysis was initiated. The rater was then asked to independently analyze the samples. Inter-rater reliability was established using the Intraclass Correlation Coefficient (ICC) using the two-way mixed model for the following variables: Accuracy measures for semantic fluency tasks (fruits and colors), phoneme fluency tasks (phoneme /n/ and phoneme /p/), alternate fluency tasks (Task 1: alternate between two semantic categories, Task 2: alternate between two phonemes, and Task 3: alternate between a semantic category and a phoneme). ICC values can range from 0 to 1, with higher values indicating better reliability. The results showed a good reliability score for the

accuracy measures of fruits (r=0.982), colors (r=0.992), phoneme /n/ (r=0.990), phoneme /p/ (r=0.995), and the following tasks of alternate fluency: Task 1 (r=0.955), Task 2 (r=0.952) and Task 3 (r=0.899). In the present study, the obtained ICC was almost >.9, indicating that the data is highly reliable.

Intra-rater reliability*:* To check for intra-rater reliability, the investigator re-analyzed 20% of the samples after a gap of three months. Intra-rater reliability was established for the following variables: Accuracy measures for semantic fluency tasks (fruits and colors), phoneme fluency tasks (phoneme /n/ and phoneme /p/), alternate fluency tasks (Task 1: alternate between two semantic categories, Task 2: alternate between two phonemes, and Task 3: alternate between a semantic category and a phoneme). The results indicated a good reliability score for the accuracy measures of fruits (r=0.992), colors (r=0.997), phoneme /n/ (r=0.994), phoneme /p/ (r=0.996), and the following tasks of alternate fluency: Task 1 (r=0.917), Task 2 (r=0.971) and Task 3 (r=0.998). Overall, good inter-rater and intra-rater reliability was observed.

The results of the present study are described under the following headings:

4.1 Performance on verbal fluency task in terms of accuracy between AHL and NTA

The first objective of the study was to compare the performance of verbal fluency tasks in terms of accuracy between AHL and NTA groups. To explore verbal fluency tasks, semantic fluency, phoneme fluency, and alternate fluency tasks were employed in the study. The results are discussed separately for all the tasks using the following headings.

4.1.1 Performance on semantic fluency tasks between AHL and NTA

In this task, accuracy was considered as the dependent variable. Semantic fluency was assessed using two categories: fruits and colors. The descriptive and inferential statistics were performed on accuracy measures in both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.1. The mean accuracy for the AHL group was 9.89 and 9.47 for the categories fruits and colors respectively. Their performance was poor compared to the NTA group for both categories including fruits (13.61) and colors (14.42). The qualitative analysis revealed notable differences in the scores for the semantic category of fruits across both groups. In the NTA group, participants 15 and 19 achieved the highest scores in this category, each with a score of 18. In contrast, participant 11 recorded the lowest score within this group, with a score of 7. Similarly, in the AHL group, Participants 5 and 9 attained the highest scores, both with a score of 13. The lowest scores in the AHL group were observed for Participants 8, 11, and 16, each of whom scored 8. It was observed that within the NTA group, Participant 1 achieved the highest score in the semantic category of colors, with a score of 20. In contrast, Participant 11 scored the lowest in this category, with a score of 7. Similarly, within the AHL group, Participant 3 obtained the highest score in the colors category, with a score of 13, while Participant 10 recorded the lowest score of 4. The performance on the semantic fluency task between AHL and NTA groups are represented in Figures 4.1 and 4.2. Although non-parametric tests were used for inferential analysis, mean-based graphical representations are presented for ease of visualization and uniformity across the study.

Table 4.1

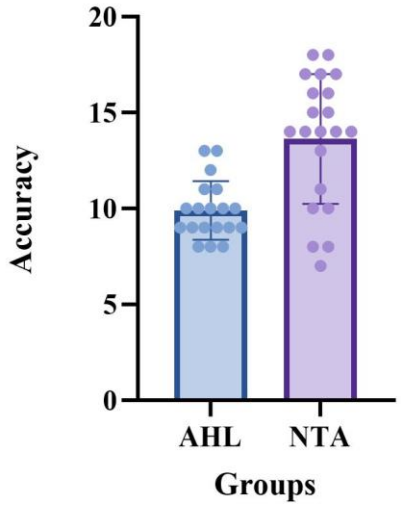
Descriptive statistics results of performance on semantic fluency task in terms of accuracy between AHL and NTA

Category	Groups	N	Mean	SD	Median	IQR	Q1	Q3
Fruits	**AHL**	19	9.89	1.52	10.00	2.00	9.00	11.00
	NTA	21	13.61	3.38	14.00	6.00	10.50	16.50
Colors	**AHL**	19	9.47	2.22	10.00	3.00	8.00	11.00
	NTA	21	14.42	4.26	14.00	4.00	12.00	16.00

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile

Figure 4.1

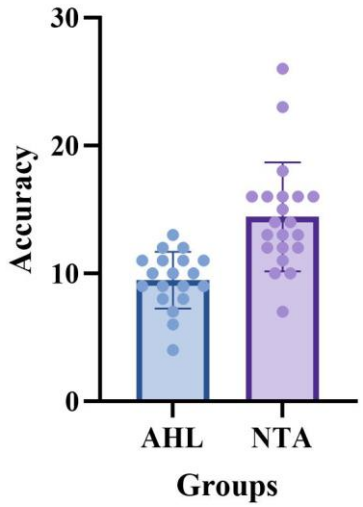
Mean accuracy of semantic fluency task in AHL and NTA for the category of fruits



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

Figure 4.2

Mean accuracy of semantic fluency task in AHL and NTA for the category of colors



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

4.1.2 Performance on phoneme fluency tasks between AHL and NTA

In this task, accuracy was considered as the dependent variable. Phoneme fluency was assessed using two phonemes: phoneme /n/ and phoneme /p/. The descriptive and inferential statistics were performed on accuracy measures in both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.2. The mean accuracy for the AHL group was 7.57 and 7.26 for the phonemes /n/ and /p/ respectively. Their performance was poor compared to the NTA group for both phonemes (phoneme /n/ =11.04, phoneme /p/ =12.09). In the NTA group, Participant 1 achieved the highest scores in the phoneme /n/, with a score of 19. In contrast, participant 14 recorded the lowest score within this group, with a score of 3. Similarly, in the AHL group, Participant 5 attained the highest score of 13. The lowest scores in the AHL group were observed for Participants 4 and 18, each of whom

scored 2. It was observed that within the NTA group, Participant 1 achieved the highest score for the phoneme /p/, with a score of 25. In contrast, Participant 17 scored the lowest in this category, with a score of 3. Similarly, within the AHL group, Participant 3 obtained the highest score for the phoneme /p/, with a score of 14, while Participants 8 and10 recorded the lowest score of 0. The performance on the phoneme fluency task between AHL and NTA groups are represented in Figures 4.3 and 4.4.

Table 4.2

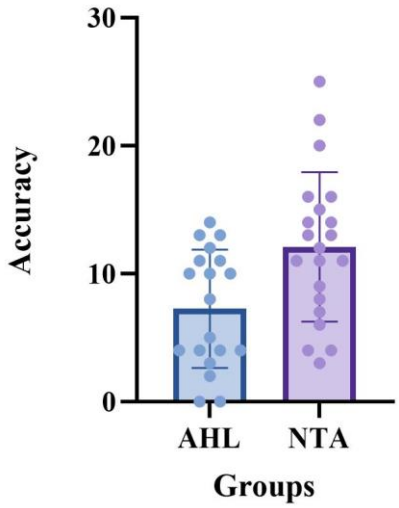
Descriptive statistics results of performance on phoneme fluency task in terms of accuracy between AHL and NTA

Phonemes	Groups	N	Mean	SD	Median	IQR	Q1	Q3
/n/	AHL	19	7.57	3.32	8.00	4.00	6.00	10.00
	NTA	21	11.04	4.37	11.00	6.50	7.50	14.00
/p/	AHL	19	7.26	4.16	8.00	7.00	4.00	11.00
	NTA	21	12.09	5.83	12.00	8.00	7.50	15.50

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile

Figure 4.3

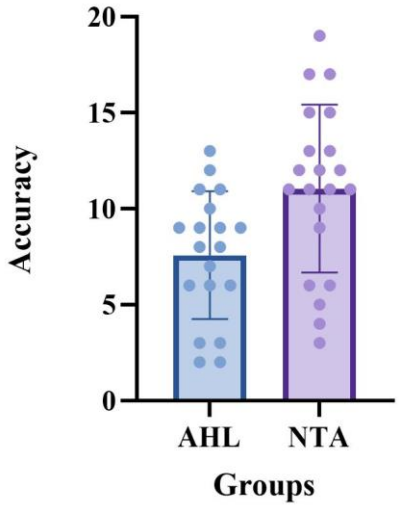
Mean accuracy of phoneme fluency task in AHL and NTA for the phoneme /p/



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

Figure 4.4

Mean accuracy of phoneme fluency task in AHL and NTA for the phoneme /n/



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

4.1.3 Performance on alternate fluency tasks between AHL and NTA

In this task, accuracy was considered as the dependent variable. Alternate fluency was assessed using three tasks: Task (1) alternate between two semantic categories: animals and vegetables, Task (2) alternate between two phonemes: /r/ and /s/, and Task (3) alternate between the semantic category of common objects and the phoneme /k/. The descriptive and inferential statistics were performed on accuracy measures in both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.3. The mean accuracy for the AHL group was 5.63, 3.00, and 3.52 for Tasks (1), (2), and (3) respectively. The NTA group performed better than the AHL group on all three tasks (Task (1) = 6.61, Task (2) = 6.71 and Task (3) = 6.66).

In Task (1), within the NTA group, Participants 3 and 7 recorded the highest scores of 10, while Participants 4 and 5 scored the lowest, with a score of 3. In the AHL group, Participant 6 achieved the highest score of 9, whereas Participant 10 obtained the lowest score of 1. In Task (2), within the NTA group, Participant 1 achieved the highest score of 11, while Participants 8 and 11 scored the lowest, with a score of 4. In the AHL group, Participant 2 recorded the highest score of 7, while Participants 10, 9, and 7 obtained the lowest scores, with a score of 0. In Task 3, within the NTA group, Participants 3, 9, and 10 achieved the highest score of 9, while Participant 17 recorded the lowest score of 4. In the AHL group, Participant 2 obtained the highest score of 7, while Participant 10 scored the lowest, with a score of 0. The performance on the alternate fluency task between AHL and NTA groups are represented in Figures 4.5, 4.6 and 4.7.

Table 4.3

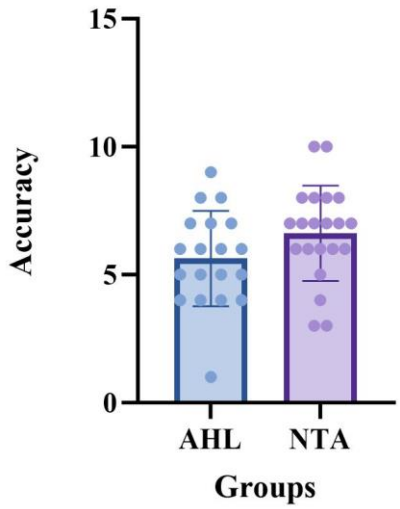
Descriptive statistics results of performance on alternate fluency task in terms of accuracy between AHL and NTA

Tasks	Groups	N	Mean	SD	Median	IQR	Q1	Q3
Task 1	**AHL**	19	5.63	1.86	6.00	3.00	4.00	7.00
	NTA	21	6.61	1.85	7.00	2.00	6.00	8.00
Task 2	**AHL**	19	3.00	2.23	3.00	4.00	1.00	5.00
	NTA	21	6.71	2.02	6.00	3.50	5.00	8.50
Task 3	**AHL**	19	3.52	1.92	3.00	4.00	2.00	6.00
	NTA	21	6.66	1.52	7.00	3.00	5.00	8.00

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile

Figure 4.5

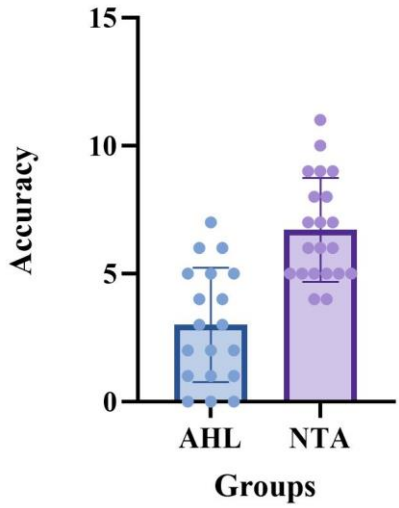
Mean accuracy of alternate fluency task in AHL and NTA for Task (1)



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

Figure 4.6

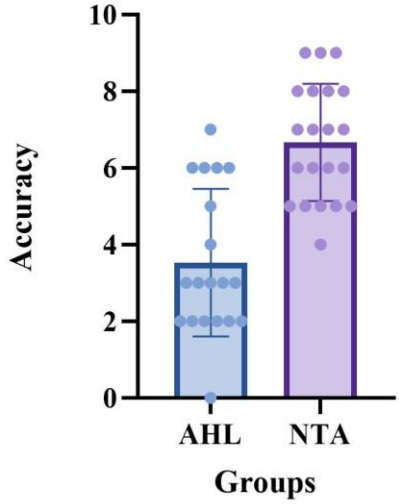
Mean accuracy of alternate fluency task in AHL and NTA for Task (2)



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

Figure 4.7

Mean accuracy of alternate fluency task in AHL and NTA for Task (3)



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

The Mann-Whitney U test was employed to compare group differences, as the data violated assumptions required for parametric analyses. The results of the Mann-Whitney U test revealed significant differences between the AHL and NTA groups for most fluency tasks as provided in Table 4.4.

Table 4.4

Mann-Whitney U test results for comparison of fluency task performance between AHL and NTA groups

	Task	Mann-Whitney U	/Z/	p	r_e
Semantic Fluency	**Fruits**	74.00	3.42	0.00	0.54
	Colors	46.00	4.17	0.00	0.66
Phoneme Fluency	**Phoneme /n/**	102.00	2.65	0.00	0.42
	Phoneme /p/	103.50	2.61	0.00	0.41
Alternate Fluency	**Task 1**	139.00	1.66	0.09	0.26
	Task 2	48.50	4.12	0.00	0.65
	Task 3	48.00	4.14	0.00	0.66

The Mann–Whitney U test revealed significant differences between the AHL and NTA groups across most fluency tasks. In semantic fluency, both Fruits (/Z/ = 3.42, p < .00, r = .54) and Colors (/Z/ = 4.17, p < .00, r = .66) demonstrated large effect sizes, indicating substantial group differences. Similarly, for phoneme fluency, significant differences were observed for phoneme /n/ (/Z/ = 2.65, p < .00, r = .42) and phoneme /p/ (/Z/ = 2.61, p < .00, r = .41), reflecting moderate effects. In the alternate fluency tasks, Task 2 (/Z/ = 4.12, p < .00, r = .65) and Task 3 (/Z/ = 4.14,

$p < .00$, $r = .66$) also showed large effect sizes, whereas Task 1 did not reach statistical significance (/Z/ = 1.66, $p = .09$, $r = .26$).

4.2 Performance on TMT-B in terms of completion time between AHL and NTA

The second objective of the study was to compare the performance of TMT-B in terms of completion time between AHL and NTA groups. In this task, completion time was considered as the dependent variable. The descriptive and inferential statistics were performed for completion time in both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.5.

The mean completion time (in seconds) for the AHL group was 125.13 whereas it was 65.56 for the NTA group. The NTA group outperformed the AHL group as the AHL group took a longer time to complete the task than the NTA group. In the NTA group, Participant 3 completed the TMT-B in the shortest duration of 40.87 seconds, while Participant 5 took the longest time, completing the task in 86 seconds. In the AHL group, the shortest completion time was recorded by Participant 1, with a duration of 71.91 seconds, whereas Participant 4 took the longest time of 224.03 seconds. It is important to note that shorter completion times indicate better cognitive flexibility. The performance of the TMT-B in terms of completion time between AHL and NTA groups is represented in Figure 4.8.

Table 4.5

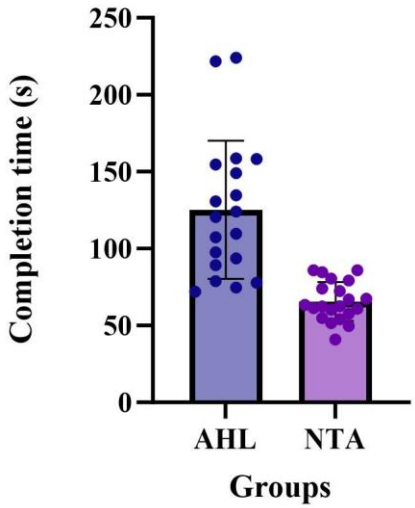
Descriptive statistics results of performance on TMT-B in terms of completion time between AHL and NTA

Task measure	Groups	N	Mean	SD	Median	IQR	Q1	Q3
Completion time (s)	AHL	19	125.13	44.89	120.62	65.43	89.23	154.66
	NTA	21	65.56	12.63	62.53	20.49	56.18	76.67

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; s = seconds; Q1 = First quartile; Q3 = Third quartile

Figure 4.8

Mean completion time of TMT-B in AHL and NTA.



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

Further, the data were subjected to a normality check using the Shapiro-Wilk test, and it was found that the data were normally distributed *(p>0.05)* in both groups.

Independent sample t-test was used to determine whether there were statistically significant differences between the means of the two independent groups. The test results revealed a statistically significant difference in the mean scores between the AHL and NTA groups (/t/ (38) = -5.83, $p < 0.01$). The mean score for AHL (M = 125.13, SD = 44.89) was significantly higher than that of NTA (M = 65.56, SD = 12.63), with a large effect size (Cohen's d = 1.80). These findings suggest that there is a statistically significant difference in completion time between the two groups. In essence, higher completion time suggests poorer cognitive flexibility as demonstrated by the AHL group when compared to the NTA group.

4.3 Performance on Stroop task in terms of accuracy and reaction time between AHL and NTA

The third objective of the study was to compare the performance of the Stroop task in terms of accuracy and reaction time (RT) between AHL and NTA groups. Accuracy was measured for all the conditions combined whereas RT was measured between the groups as (1) Average RT, (2) RT for congruent and incongruent conditions, and (3) Stroop effect. The results are discussed separately for accuracy and RT measures for the Stroop task using the following headings.

4.3.1 Performance on Stroop task in terms of accuracy between AHL and NTA

In this task, accuracy was considered as the dependent variable. The descriptive and inferential statistics were performed on accuracy measures in both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.6. The mean accuracy values for the AHL group (27.89) were lesser than the NTA group (39.38). In this task, the majority of participants in the NTA group achieved the highest score of 40, including Participants 1, 2, 3, 4, 6, 7, 10, 11, 13, 16, 17, 18, and

21. The lowest score of 37 was obtained by Participant 9. In the AHL group, Participants 7, 12, and 17 achieved the highest score of 40, while Participant 1 recorded the lowest score of 10. The performance on the Stroop task in terms of accuracy between AHL and NTA groups is represented in Figure 4.9.

Table 4.6

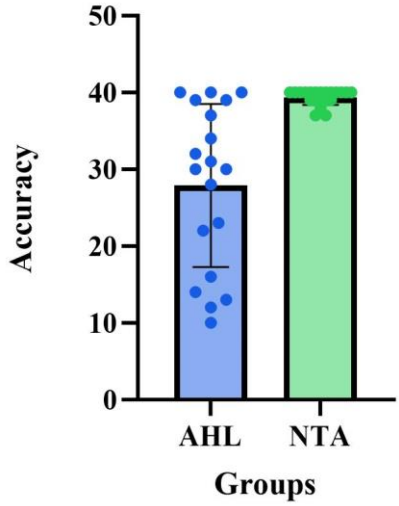
Descriptive statistics results of performance on Stroop task in terms of accuracy between AHL and NTA

Task Measure	Groups	N	Mean	SD	Median	IQR	Q1	Q3
Accuracy	**AHL**	19	27.89	10.61	30.00	23.00	16.00	39.00
	NTA	21	39.38	0.97	40.00	1.00	39.00	40.00

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile

Figure 4.9

Mean accuracy of Stroop task in AHL and NTA



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

Further, the data were subjected to a normality check using the Shapiro-Wilk test, and it was found that the data were not normally distributed *(p<0.05)* in both groups. Subsequently, the Mann-Whitney U test was performed to determine the difference between the two groups. A significant difference was seen between the two groups for accuracy measure of the Stroop task ($|Z| = 4.04$, $p < 0.01$, $r = 0.63$) with a high effect size.

4.3.2 Performance on Stroop task in terms of Average RT between AHL and NTA

In this task, Average RT was considered as the dependent variable. Average RT is the combined RT for both congruent and incongruent conditions. The descriptive and inferential statistics were performed on Average RT measures for both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.7. The mean values for Average RT for the AHL group (2257.42 ms) were higher than the NTA group (1578.14 ms). In the NTA group, Participant 4 recorded the shortest RT of 1210 ms, while Participant 14 had the longest RT, with a duration of 2119 ms. In the AHL group, Participant 11 achieved the shortest RT of 1470 ms, while Participant 8 recorded the longest RT of 3334 ms. Shorter reaction times indicate better performance, suggesting that participants with quicker reaction times are more efficient in completing the task. The performance on the Stroop task in terms of Average RT between AHL and NTA groups is represented in Figure 4.10.

Table 4.7

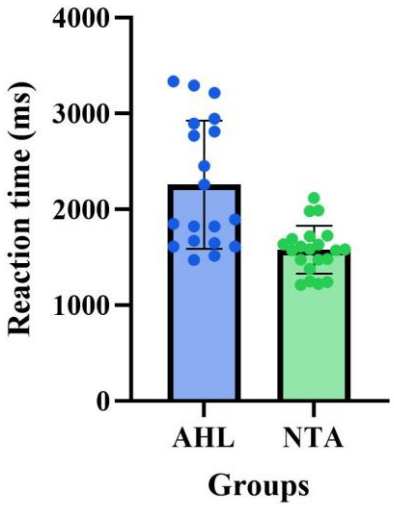
Descriptive statistics results of performance on Stroop task in terms of Average RT between AHL and NTA

Task measure	Groups	N	Mean	SD	Median	IQR	Q1	Q3
Average RT (ms)	AHL	19	2257.42	667.59	1895.00	1247.00	1649.00	2896.00
	NTA	21	1578.14	249.16	1582.00	277.50	1427.00	1704.50

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile; ms = milliseconds

Figure 4.10

Mean Average RT of Stroop task in AHL and NTA



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; ms = milliseconds

Further, the data were subjected to a normality check using the Shapiro-Wilk test, and it was found that the data were not normally distributed *($p<0.05$)* in both groups. Subsequently, the Mann-Whitney U test was performed to determine the difference between the two groups. A significant difference was seen between the two

groups for the Average RT of the Stroop task ($|Z| = 3.53$, $p < 0.01$, $r = 0.55$) with a high effect size. These results imply that the two groups differ significantly in their average RT on the Stroop task, with the NTA group responding noticeably faster than the AHL group.

4.3.3 Performance on Stroop task in terms of RT for congruent and incongruent conditions between AHL and NTA

In this task, RT for congruent condition (congRT) and RT for incongruent condition (incongRT) were considered as dependent variables. The descriptive and inferential statistics were performed on congRT and incongRT for both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.8. The mean values of congRT for the AHL group (2127.89 ms) were higher than the NTA group (1432.23 ms). The mean values of incongRT for the AHL group (2355.36 ms) were also higher than the NTA group (1650.71 ms). In the NTA group, for congruent RT, Participant 5 recorded the shortest RT of 1061 ms, while Participant 9 had the longest RT at 1713 ms. In the AHL group, Participant 4 achieved the shortest RT of 1459 ms, while Participant 3 had the longest RT of 2895 ms. For incongruent RT in the NTA group, Participant 10 recorded the shortest RT of 1198 ms, while Participant 12 had the longest RT of 2224 ms. In the AHL group, Participant 2 achieved the shortest RT of 1653 ms, and Participant 3 had the longest RT of 3259 ms. Shorter reaction times indicate better performance, suggesting that participants with quicker reaction times are more efficient in completing the task. The performance on the Stroop task in terms of RT for congruent and incongruent conditions between AHL and NTA groups are represented in Figures 4.11 and 4.12.

Table 4.8

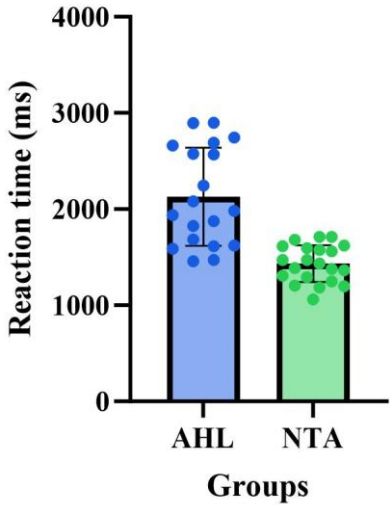
Descriptive statistics results of performance on Stroop task in terms of RT for congruent and incongruent conditions between AHL and NTA

Task measure	Groups	N	Mean	SD	Median	IQR	Q1	Q3
congRT (ms)	**AHL**	19	2127.89	509.28	1982.00	1039.00	1623.00	2662.00
	NTA	21	1432.23	192.11	1436.00	334.00	1270.50	1604.50
incongRT (ms)	**AHL**	19	2355.36	511.13	2347.00	704.00	1998.00	2702.00
	NTA	21	1650.71	223.19	1656.00	217.00	1551.00	1768.00

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile; ms = milliseconds

Figure 4.11

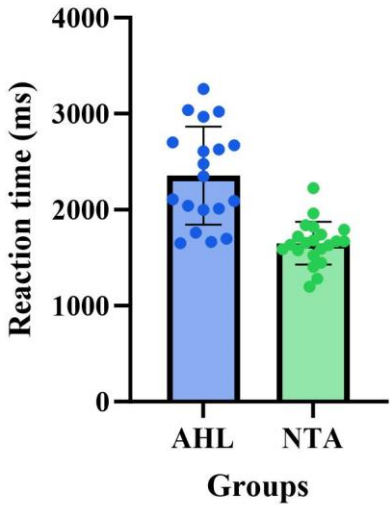
Mean RT of Stroop task for congruent conditions in AHL and NTA



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; ms = milliseconds

Figure 4.12

Mean RT of Stroop task for incongruent conditions in AHL and NTA



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; ms = milliseconds

Further, the data were subjected to a normality check using the Shapiro-Wilk test, and it was found that the data were normally distributed *(p>0.05)* in both groups. One-way MANOVA was used to determine whether there were significant differences between the groups. The results indicated statistically significant differences between the groups for congRT and incongRT measures (F (2,37) = 17.36, $p < 0.01$, Wilk's $\Lambda = 0.51$, $\eta_p^2 = 0.48$). This large effect size indicates a higher difference between the two groups.

Subsequent univariate ANOVA was carried out separately for both congRT and incongRT measures. Results indicated that there were statistically significant differences in the RT in both congruent (F (1,38) = 33.92, $p < 0.01$, $\eta_p^2 = 0.47$) and incongruent conditions (F (1,38) = 33.02, $p < 0.01$, $\eta_p^2 = 0.46$) on the Stroop task

between the groups. This finding implies that the groups likely vary in inhibitory control. The significant differences in both congruent and incongruent conditions suggest that the NTA group has better inhibitory control in both conditions.

4.3.4 Performance on Stroop task in terms of Stroop effect between AHL and NTA

In this task, the Stroop effect was considered as the dependent variable. Descriptive and inferential statistics were performed for the Stroop effect for both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.9. The mean values of the Stroop effect for the AHL group (227.00 ms) were higher than the NTA group (218.47 ms). Within the NTA group, Participant 20 recorded the shortest reaction time of 9 ms, while Participant 12 had the longest RT of 663 ms. In the AHL group, Participant 9 achieved the shortest RT of 26 ms, while Participant 18 recorded the longest RT of 654 ms. The performance on the Stroop task in terms of Stroop effect between AHL and NTA groups is represented in Figure 4.13.

Table 4.9

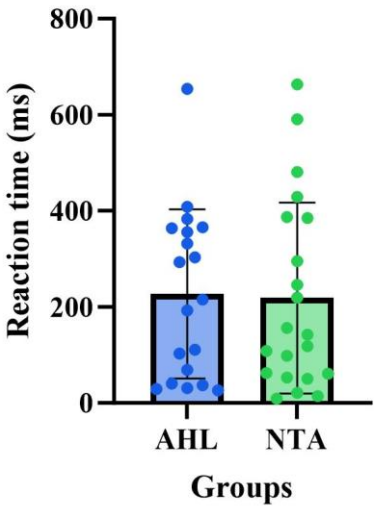
Descriptive statistics results of performance on Stroop task in terms of Stroop effect between AHL and NTA

Task measure	Groups	N	Mean	SD	Median	IQR	Q1	Q3
Stroop effect (ms)	**AHL**	19	227.00	176.30	215.00	324.00	40.00	364.00
	NTA	21	218.47	198.57	142.00	329.00	57.00	386.00

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile; ms = milliseconds

Figure 4.13

Mean Stroop effect in AHL and NTA



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; ms = milliseconds

Further, the data were subjected to a normality check using the Shapiro-Wilk test, and it was found that the data were not normally distributed *($p<0.05$)* in both groups. Subsequently, the Mann-Whitney U test was performed to determine the difference between the two groups. No significant difference was found between the two groups for Stroop effect ($|Z|$ =0.12, p > 0.01, r = 0.01*)*. The lack of significant difference between the two groups for the Stroop effect suggests that, despite differences in reaction times for the congruent and incongruent conditions individually, both groups exhibit similar levels of interference when switching from congruent to incongruent tasks. The Stroop effect typically reflects the additional cognitive effort needed to manage conflicting information (incongruent condition vs. congruent condition), so this result implies that both groups handle interference similarly and that neither group has a distinct advantage in cognitive flexibility or inhibitory control specifically related to the Stroop effect. In essence, while the groups may differ in their

overall reaction speeds, their ability to manage interference does not appear to differ significantly.

4.4 Performance on Go/NoGo task in terms of accuracy and reaction time between AHL and NTA

The fourth objective of the study was to compare the performance of the Go/NoGo task in terms of accuracy and RT between AHL and NTA groups. The results are discussed separately for accuracy and RT measures for the Go/NoGo task using the following headings.

4.4.1 Performance on Go/NoGo task in terms of accuracy between AHL and NTA

In this task, accuracy was considered as the dependent variable. The descriptive and inferential statistics were performed for accuracy in both groups. The descriptive statistics for both AHL and NTA groups were computed and presented in Table 4.10. The mean value for the accuracy for the AHL group was 24.57 whereas it was 25 for the NTA group. Both the groups performed almost similarly however, the NTA group performed slightly better than the AHL group. The performance on Go/NoGo task in terms of accuracy for both groups is presented in Figure 4.14.

Table 4.10

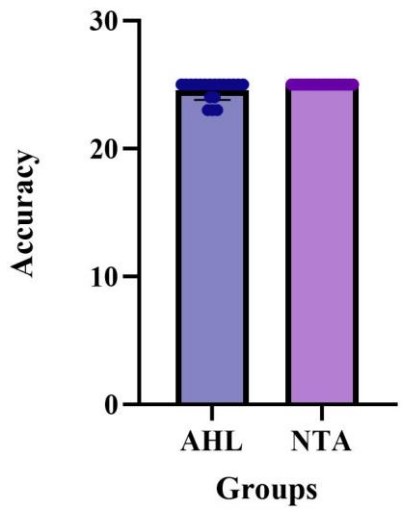
Descriptive statistics results of performance on Go/NoGo task in terms of accuracy between AHL and NTA

Task measure	Groups	N	Mean	SD	Median	IQR	Q1	Q3
Accuracy	AHL	19	24.57	0.76	25.00	1.00	24.00	25.00
	NTA	21	25.00	0	25.00	0	25.00	25.00

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile

Figure 4.14

Mean accuracy of the Go/NoGo task in AHL and NTA



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

Further, the data were subjected to a normality check using the Shapiro-Wilk test, and it was found that the data were not normally distributed *($p<0.05$)* in both groups. Since the median in both groups is the same, the comparison was not carried out. Hence, there is no significant difference found in terms of accuracy on the Go/NoGo task between the groups.

4.4.2 Performance on Go/NoGo task in terms of RT between AHL and NTA

In this task, RT was considered as the dependent variable. Descriptive and inferential statistics were performed for RT in both groups. The mean, standard deviation, median, and interquartile range for both AHL and NTA groups were computed and presented in Table 4.11. The mean value of the RT for the AHL group (in ms) was 790.84 whereas it was 560.23 for the NTA group. Within the NTA group, Participant 2 recorded the shortest reaction time of 384 ms, while Participant 4 had the longest RT of 804 ms. In the AHL group, Participant 9 achieved the shortest RT of 428 ms, while Participant 8 recorded the longest RT of 1183 ms. The AHL group had increased RT on the Go/NoGo task compared to the NTA group. The performance of the Go/NoGo task in terms of RT between AHL and NTA groups is represented in Figure 4.15.

Table 4.11

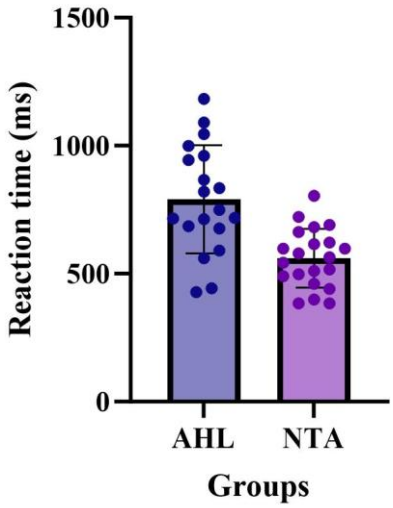
Descriptive statistics results of performance on Go/NoGo task in terms of RT between AHL and NTA

Task measure	Groups	N	Mean	SD	Median	IQR	Q1	Q3
RT (ms)	AHL	19	790.84	210.91	749.00	284.00	677.00	961.00
	NTA	21	560.23	114.83	564.00	166.50	476.00	642.50

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults; SD = Standard deviation; IQR = Interquartile range; Q1 = First quartile; Q3 = Third quartile; ms = millisecond

Figure 4.15

Mean RT of the Go/NoGo task in AHL and NTA



Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

Further, the data were subjected to a normality check using the Shapiro-Wilk test, and it was found that the data were normally distributed *(p>0.05)* in both groups. An independent sample t-test was used to determine whether there were statistically significant differences between the means of the two independent groups. The test results revealed a statistically significant difference in the mean scores between the AHL and NTA groups (/t/ (38) = -4.35, $p < 0.01$). The mean score for AHL (M = 790.84, SD = 210.91) was significantly higher than that of NTA (M = 560.23, SD = 114.83), with a large effect size (Cohen's d = 1.35). These findings suggest a statistically significant difference in RT between the two groups. The statistically significant difference in mean scores between the AHL and NTA groups indicates that the AHL group scored significantly higher on the measured variable than the NTA group. With the AHL group's mean much higher than the NTA group's mean, it implies that participants in the AHL group perform differently—presumably less efficiently

compared to those in the NTA group. This could reflect differences in inhibitory control abilities, with the AHL group showing a tendency toward higher scores, potentially indicating slower performance.

4.5 Relationship between outcome measures of Verbal fluency test, Trail making test B, Stroop task and Go/NoGo task

The fifth objective was to investigate the relationship between the outcome measures of all the tasks considered in the study. To study the correlation between outcome measures, Spearman's rank correlation coefficient was used. Only the following pairs of outcome measures were found to have significant correlation in the clinical (AHL) and normal (NTA) groups that have been presented in Table 4.12 and Table 4.13 respectively.

Table 4.12

Correlation between outcome measures in the AHL group

Outcome measures	ρ	p
FA-CA	.54	0.01
FA-PA	.487	0.02
CA-NA	.528	0.01
CA-PA	.538	0.01
CA-AF(2)	.508	0.01
CA-AF(3)	.433	0.05
NA-PA	.744	0
AF(2)-SART	-.509	0.01
AF(3)-GNRT	.539	0.01
SCRT-SIRT	.486	0.02
SCRT-SE	-.457	0.03
SCRT-GNRT	-.439	0.04

Note. FA=Fruits Accuracy; CA=Colors Accuracy; PA=Phoneme /p/ Accuracy; NA=Phoneme /n/ Accuracy; AF(2)= Alternate Fluency Task (2) Accuracy; AF(3)= Alternate Fluency Task (3) Accuracy; SART=Stroop Average Reaction Time; GNRT= Go/NoGo Reaction Time; SCRT=Stroop Congruent condition Reaction Time; SIRT=Stroop Incongruent condition Reaction Time; SE=Stroop Effect

Table 4.13

Correlation between outcome measures in the NTA group

Outcome measures	ρ	p
CA-NA	.568	0.01
CA-PA	.492	0.03
NA-AF(2)	.535	0.01
PA-AF(2)	.594	0.00
AF(2)-AF(3)	.630	0.00
SCRT-SIRT	.935	0.00
SIRT-GNRT	.458	0.04

Note. CA=Colors Accuracy; PA=Phoneme /p/ Accuracy; NA=Phoneme /n/ Accuracy; AF(2)= Alternate Fluency Task (2) Accuracy; AF(3)= Alternate Fluency Task (3) Accuracy; GNRT= Go/NoGo Reaction Time; SCRT=Stroop Congruent condition Reaction Time; SIRT=Stroop Incongruent condition Reaction Time

4.6 Association between groups and health & lifestyle related factors

The sixth objective was to investigate the association between groups and health & lifestyle related factors. Chi-square test was used to examine the association between groups and health & lifestyle related factors. No significant association was found between the groups and any health & lifestyle related factors including hypertension χ^2 (1)=0.014, p=0.906, diabetes χ^2 (1)=2.707, p=0.100, smoking χ^2 (1)=0.011, p=0.916, alcohol consumption χ^2 (1)=1.040, p=0.308 and physical exercise χ^2 (1)=0.382, p=0.536.

In a nutshell, the study's findings indicated a significant difference in most of the outcome measures between the AHL and NTA groups indicating significant differences in performances between both groups. The overall summary of the results of the outcome measures along with the status of the null hypothesis in relation to the objectives of the study are provided in Table 4.14.

Table 4.14

Summary of analysis with their status of the null hypothesis for various outcome measures

Sl No	**Null hypotheses**	**Significant difference computed through statistical comparisons *Present/absent***	**Null hypotheses *Accepted/rejected***
1	There is no statistically significant difference in the performance of verbal fluency in terms of accuracy between adults with hearing loss and neurotypical adults. a) There is no statistically significant difference in the performance of semantic fluency in terms of accuracy between adults with hearing loss and neurotypical adults.	*Present*	*Rejected*
	b) There is no statistically significant difference in the performance of phoneme fluency in terms of accuracy between adults with hearing loss and neurotypical adults.	*Present*	*Rejected*
	c) There is no statistically significant difference in the performance of alternate fluency in terms of accuracy between adults with hearing loss and neurotypical adults.	*Present*	*Rejected*

2	There is no statistically significant difference in the performance on Trail making test B in terms of completion time between adults with hearing loss and neurotypical adults.	*Present*	*Rejected*
3	There is no statistically significant difference in the performance on the Stroop task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults. a)There is no statistically significant difference in the performance in terms of accuracy between adults with hearing loss and neurotypical adults.	*Present*	*Rejected*
	b)There is no statistically significant difference in the performance in terms of average reaction time between adults with hearing loss and neurotypical adults.	*Present*	*Rejected*
	c)There is no statistically significant difference in the performance in terms of reaction time in congruent and incongruent conditions between adults with hearing loss and neurotypical adults.	*Present*	*Rejected*
	d)There is no statistically significant difference in the performance of the Stroop effect between adults with hearing loss and neurotypical adults.	*Absent*	*Accepted*

4	There is no statistically significant difference in the performance on the Go/NoGo task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults. a)There is no statistically significant difference in the performance of the Go/NoGo task in terms of accuracy between adults with hearing loss and neurotypical adults.	*Absent*	*Accepted*
	b)There is no statistically significant difference in the performance of the Go/NoGo task in terms of reaction time between adults with hearing loss and neurotypical adults.	*Present*	*Rejected*
5	There is no significant correlation between outcome measures of the Verbal fluency test, Trail making test B, Stroop task, and Go/No Go task.	*Present*	*Rejected*
6	There is no significant association between groups and health & lifestyle-related factors in each of the outcome measures.	*Absent*	*Accepted*

Chapter 5

Discussion

Age-related hearing loss (ARHL) is a prevalent chronic condition among older adults, characterized primarily by peripheral hearing dysfunction (Collins, 1997; Cruickshanks et al., 2003; Quaranta et al., 2014). In addition to these auditory changes, accumulating evidence indicates that individuals with ARHL also experience cognitive alterations (Bush et al., 2015; Deal et al., 2017; Humes, 2013; Lin, 2011; Lin et al., 2013; Ronnberg et al., 2011). Recent studies indicate that even mild hearing loss can lead to changes in cognitive control (Lin et al., 2013; Valentijn et al., 2005). Cognitive control or executive function (EF), encompasses the cognitive processes that oversee and coordinate cognitive activities to manage and regulate behavior aimed at achieving specific goals (Baddeley, 2012; Diamond, 2013; Petersen & Posner, 2012; Snyder et al., 2014). Three frequently discussed processes within cognitive control are cognitive flexibility, inhibitory control, and working memory updating (Diamond, 2013; Miyake et al., 2000). In brief, cognitive flexibility aids in shifting between tasks or mental sets, inhibitory control allows for the suppression of irrelevant information and responses, and working memory updating facilitates the updating and maintenance of incoming information over short periods. Alterations in cognitive control associated with normal cognitive aging are well-documented (Baddeley, 2012; Hasher, 1988). Increasing evidence suggests that these alterations may be more pronounced in individuals with ARHL (Uchida et al., 2019). Hence the current study was carried out to understand these cognitive control processes in adults with hearing loss.

The present study aimed to investigate cognitive flexibility and inhibitory control in adults with hearing loss. A standard group comparison was carried out

between 21 adults with normal hearing (NTA group) and 19 adults with bilateral mild sensorineural hearing loss (AHL group). Data obtained from the participants were analyzed to assess the study objectives and hypotheses. The findings of the study are summarized in the previous chapter. The results showed a substantial difference in the performance on most of the tasks between the normal and clinical groups. Furthermore, the outcomes of the study are discussed under the following headings

1. Performance on verbal fluency task in terms of accuracy between adults with hearing loss and neurotypical adults
2. Performance on Trail making test-B (TMT-B) in terms of completion time between adults with hearing loss and neurotypical adults
3. Performance on the Stroop task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults
4. Performance on the Go/NoGo task in terms of accuracy and reaction time between adults with hearing loss and neurotypical adults
5. Correlation between outcome measures of verbal fluency, TMT-B, Stroop task and Go/NoGo task
6. Association between groups and health & lifestyle related factors

5.1 Performance on verbal fluency task in terms of accuracy between AHL and NTA

The first objective of the study was to compare the performance on verbal fluency tasks in terms of accuracy between AHL and NTA groups. To explore verbal fluency tasks, semantic fluency, phoneme fluency, and alternate fluency tasks were employed in the study. In this task, accuracy was considered as the dependent variable. Semantic fluency was assessed using two categories: fruits and colors. It was found

that there were significant differences in the accuracy of both fruits and colors between the groups. The AHL group performed poorly than the NTA group. Phoneme fluency was assessed using two phonemes: phoneme /n/ and phoneme /p/. Results indicated significant differences in the accuracy of both phonemes /n/ and /p/ between the groups. The AHL group again performed poorer than the NTA group. Alternate fluency was assessed using three tasks: Task (1) alternate between two semantic categories: animals and vegetables, Task (2) alternate between two phonemes: /r/ and /s/, and Task (3) alternate between the semantic category of common objects and the phoneme /k/. Results indicated that there were significant differences in the accuracy of alternate fluency for Tasks (2) and (3) between the two groups where the AHL group was outperformed by the NTA group. These findings are in line with previous studies that proved that verbal fluency tasks can be used to identify cognitive impairment, as well as to assess the effectiveness of language tests in predicting cognitive decline.

In an observational cross-sectional study, verbal fluency tasks were analyzed among participants, which included cognitively healthy controls, individuals with mild cognitive impairment (MCI), and patients with mild Alzheimer's disease (AD). The findings revealed that errors and repetitions in the phonemic task were the most significant variables associated with MCI and AD (Wajman & Cecchini, 2023). Another case-control study involving participants with MCI was followed up for 2 years using verbal fluency discrepancy scores to predict the progression to AD. Verbal fluency discrepancy scores, calculated by subtracting phonemic fluency from semantic fluency at baseline, revealed that those who progressed to AD had significantly lower scores compared to those who retained an MCI diagnosis and normal participants. Logistic regression analysis showed that each unit decrease in the

discrepancy score increased the odds of progressing to AD by 9%. The findings suggest that individuals with MCI who exhibit poor verbal fluency scores should be closely monitored, as they are at a higher risk of progressing to AD (Vaughan et al., 2018).

A five-year longitudinal study that also used semantic-phonological delta (SPD), which reflects the discrepancy between categorical and phonological verbal fluency showed that among those with MCI, those who progressed to dementia had significantly lower SPD scores compared to those who did not progress (Marra et al., 2021). These studies have explored verbal fluency tasks as predictors of further cognitive decline. However, there is a relative scarcity of research examining the use of verbal fluency tasks to predict cognitive decline in adults with hearing loss. One study examined verbal fluency in older adults with acquired sensorineural hearing impairment and found no significant link between hearing loss and performance on semantic fluency tasks (Maseda et al., 2014). However, an association was observed with letter fluency tasks (Classon et al., 2014), indicating that individuals with hearing loss might have less flexible phonological processing. It was suggested that phoneme fluency is more sensitive to acquired hearing loss compared to semantic fluency.

On similar lines, Irace et al. (2022) investigated the association between subclinical hearing loss and cognitive decline among cognitively normal adults aged 50 years and older, using data from the Baltimore Longitudinal Study of Aging. Results revealed that a 10-dB increase in hearing loss was associated with an annual decline in letter fluency test scores. A recent study assessing cognitive flexibility in adults with and without hearing loss also found significant differences between the hearing loss and normal hearing groups on phoneme fluency tests (Shende et al.,

2021). However, in the present study, significant differences were observed between the normal and clinical groups for both semantic and phoneme fluency tasks. On the contrary, a group of researchers investigated the impact of self-reported hearing loss on longitudinal cognitive function in a cohort of 579 late middle-aged adults without clinical impairment, drawn from the Wisconsin Registry for Alzheimer's Prevention (WRAP). It was found that participants with self-reported hearing loss performed significantly poorer on speed and flexibility measures compared to those without hearing loss, with no significant association observed for visuospatial memory or verbal fluency (Fields et al., 2020).

On the other hand, alternate fluency test is used for assessing extradimensional shifting, a cognitive process that involves switching attention between different tasks or concepts. This test helps evaluate an individual's ability to shift focus from one set of rules or categories to another, providing insights into cognitive flexibility and EF. The phonemic/semantic alternate fluency test was designed to assess shifting aptitude by requiring participants to generate words based on alternating phonemic and semantic cues, which were previously used in separate fluency subtests. This approach minimizes the effort needed to access responses but requires rapid mental set shifting to alternate between phonemic and semantic criteria. As a result, this task effectively measures the ability to change mental sets. Nevertheless, the fixed order in which the three fluency subtests are administered may influence the shifting cost experienced by participants when transitioning from the single fluency tasks to the alternate fluency task (Costa et al., 2014). Significant group differences were found for alternate fluency tasks in the present study indicating poorer cognitive flexibility in the hearing loss group. Hence, the poorer performance of the hearing loss group compared to the normal hearing group suggested reduced cognitive flexibility in adults with hearing loss in the

current study. This finding aligns with the most recent study that explored verbal fluency tasks in individuals with hearing loss which found that poor hearing contributes to reduced cognitive flexibility (Chandrashekar & Nagaraj, 2024c).

Verbal fluency tasks are also commonly used in neuropsychological assessments to evaluate both verbal ability (VA) and executive control ability (EA) (Shao et al., 2014). The performance on verbal fluency tasks is believed to reflect a combination of VA and EA skills. VA encompasses vocabulary knowledge and lexical access speed, while EA includes aspects like working memory, inhibition, and cognitive flexibility. Verbal fluency tasks are thought to engage working memory as participants need to remember the instructions, suppress irrelevant responses, and switch between word categories (Henry & Crawford, 2004). Inhibition plays a role in filtering out irrelevant responses and preventing repetition during these tasks (Hirshorn & Thompson-Schill, 2006). The ability to switch between different word categories also indicates cognitive flexibility, a component of EA (Abwender et al., 2001). This interplay of cognitive processes during verbal fluency tasks highlights the complex nature of the assessment and the need to consider both VA and EA in interpreting performance (Shao et al., 2014).

Additionally, verbal fluency has been linked to fluid intelligence, suggesting that individuals with higher cognitive abilities may perform better on these tasks (Roca et al., 2012). The multifaceted demands of verbal fluency tasks make them a valuable tool for assessing various cognitive functions, making them suitable for research and clinical purposes (Ettenhofer et al., 2006). As such, understanding the predictors that influence performance in these tasks can provide valuable insights into the underlying cognitive processes involved in verbal fluency (Shao et al., 2014).

The significant difference observed in the present study not only suggests that cognitive flexibility is impaired in the hearing loss group, but also indicates that this impairment may be mediated by other cognitive processes. For example, in the semantic fluency task, individuals in the AHL group demonstrated significantly lower scores for both the fruits and colors categories. This supports previous research indicating that hearing loss can negatively affect semantic memory and word retrieval abilities (Loughrey et al., 2018) suggesting that these processes could be compromised. Word retrieval processes may rely on either phonological or semantic searches, each placing unique demands on respective processing systems (Costafreda et al., 2006; Gourovitch et al., 2000).

Interestingly, while the current study found significant group differences in semantic fluency, this contrasts with earlier studies that reported no such differences (Classon et al., 2014; Shende et al., 2021; van Hooren et al., 2007), which typically observed disparities in phonemic rather than semantic fluency. The present findings align with literature suggesting that hearing loss impairs phonological representations and their manipulation, resulting in reduced performance in phonemic fluency tasks (Anderson, 2002; Anderson & Lyxell, 1998).

The current study also identified significant group differences in alternate fluency tasks, potentially due to increased cognitive demands associated with shifting between phonemic and semantic categories. Alternate fluency tasks assess two main types of cognitive shifting (Downes et al., 1993): intra-dimensional shifting, which involves alternation within the same category, and extra-dimensional shifting, which requires transitioning between different categories (e.g., from a semantic group to a phoneme-based group). These shifts may rely on different cognitive rules—shifting

within the same domain requires a single set of rules, while switching between domains demands managing two separate sets of rules. This added complexity increases executive function demands, possibly contributing to the AHL group's lower performance in alternate fluency tasks. Hence, the present findings support the utility of verbal fluency tasks as sensitive indicators of cognitive impairment. Verbal fluency engages multiple cognitive domains, including semantic memory, working memory, and executive functions, making it particularly vulnerable to early cognitive decline (Lezak et al., 2012; Maseda et al., 2014; Strauss et al., 2006). This highlights the complex interaction between hearing loss and various cognitive domains, emphasizing the need for a more comprehensive understanding of how hearing loss affects overall cognitive function.

Although alternate fluency tasks are generally considered to impose greater cognitive demands than single-category fluency tasks due to increased requirements for working memory, cognitive flexibility, and inhibitory control, alternative explanations from models of lexical access should also be considered. According to the Lexical Competition Model, retrieval latency increases when multiple semantically related candidates are activated simultaneously, resulting in greater competition during word selection (Dell, 1986; Levelt, 1999). In this context, alternating between categories may reduce intra-category competition by limiting the number of closely related lexical neighbours activated at any given time, potentially facilitating retrieval despite increased executive demands. Similarly, the Neighbourhood Density Model proposes that words from dense lexical neighbourhoods experience greater competition, which can influence retrieval efficiency (Luce & Pisoni, 1998). The present findings may therefore reflect an

interaction between executive control demands and lexical competition mechanisms, rather than task difficulty alone.

5.2 Performance on Trail making test-B in terms of completion time between AHL and NTA

The second objective of the study was to compare the performance of TMT-B in terms of completion time between AHL and NTA groups. The TMT is a commonly used tool to assess for brain damage or dementia. It has two parts: TMT-A and TMT-B. In TMT-A, the individual must quickly connect numbers in numerical order that are randomly scattered across the page. TMT-B, on the other hand, requires the person to alternate between connecting numbers and letters in sequence (e.g., 1-A-2-B-3-C). The time taken to finish each part is recorded as the score. TMT-A primarily measures visual scanning ability and motor skills, while TMT-B also evaluates cognitive flexibility, making it a useful indicator of executive function. Hence, TMT-B was considered in the present study to align with the aim of the study. Significant differences were found between the two groups where the NTA group outperformed the AHL group.

The reason for such an outcome can be multifaceted such as the influence of age and educational level on the time to complete the TMT have been widely reported. Most studies have examined how age affects the time to complete TMT; these studies have concluded that the time for TMT completion increases with age. In contrast, conclusions regarding the influence of educational level on the TMT have been inconsistent between studies; some studies have shown that educational level affects TMT-B, with the time for completion of TMT-B being shorter for persons of higher

educational level (Bornstein & Suga, 1988; Ernst, 1987; Ivnik et al., 1996; Tombaugh, 2004).

A study reported significant differences in the time taken to complete TMT-B between individuals with 8 years of education and those with 10 or more years. This finding aligned with earlier studies, particularly those involving participants with higher levels of education. It was concluded that individuals with more than 8 years of education tend to finish TMT-B more quickly than those with fewer years of education (Hashimoto et al., 2006). To eliminate this, participants with more than 12 years of education were considered in the present study. However, significant differences were still present in the study between the two groups. Additionally, a large-scale study by Tombaugh (2004) indicated that TMT-B performance is influenced by both age and education, with education having a particularly significant impact on adults over 54 years of age. However, in the present study, only participants under 55 were included, making the impact of age negligible.

Longitudinal research has demonstrated that the TMT can predict clinical and functional changes in patients with AD and MCI. TMT-B performance has also been utilized to distinguish individuals with AD from those with normal cognition, with TMT-B being a more reliable indicator than TMT-A for differentiating AD from normal cognition. A prior study found that the time taken to complete TMT-B is a significant independent measure, useful for identifying individuals who should be referred for dementia evaluation (Ashendorf et al., 2008). Research demonstrating the TMT's sensitivity to preclinical changes in AD (Chen et al., 2000, 2001) underscores the importance of considering TMT in identifying cognitive changes in adults with and

without hearing loss. This could be one of the possible reasons for finding a significant difference between the groups in the present study.

From a neuroanatomical perspective, performing the TMT engages the right inferior medial frontal cortex, along with other non-frontal brain regions such as the left precentral gyrus, angular gyrus, medial temporal gyrus, and the intraparietal sulcus (Jacobson et al., 2011). Research indicates that the execution of the TMT involves various cognitive functions and necessitates the activation of multiple brain regions (Oosterman et al., 2010; Terada et al., 2013). Therefore, atrophy or dysfunction in the frontal lobe might be indicated by the TMT-B score, making it a potential marker of executive function. Additionally, increased TMT-B completion times and reduced thickness in frontal, temporal, and inferior parietal regions, as well as compromised integrity of the right uncinate and thalamic radiation in older adults has been reported (MacPherson et al., 2002).

The TMT is also known for its sensitivity to cognitive impairments in various patient groups (Larrabee et al., 2008; Strauss et al., 2006). It has been used, for instance, to assess MCI and neurodegenerative diseases like AD (Ashendorf et al., 2008; Lezak et al., 2004). Longitudinal research has demonstrated that the TMT can predict clinical and functional changes in patients with AD (Chen et al., 2001), depression (Potter et al., 2013), MCI (Chapman et al., 2011; Ewers et al., 2012; Gomar et al., 2011), brain injuries (Hanks et al., 2008), and stroke (Wiberg et al., 2012).

In clinical evaluations of elderly individuals, the TMT can help differentiate between healthy individuals and those with neurological conditions (Bell-McGinty et al., 2002; Dawson et al., 2009). However, the utilization of TMT in distinguishing adults with and without hearing loss is underexamined. One longitudinal study on

community-dwelling older adults used TMT-B and found a significant association between hearing impairment and accelerated cognitive decline. Specifically, even mild hearing impairment was linked to steeper declines in cognitive function, with more pronounced effects observed in individuals with moderate to severe impairment (Alattar et al., 2020). Another study by Shende et al. (2021) also found significant differences in TMT-B completion time between participants with and without hearing loss highlighting the cognitive flexibility deficits in AHL. The most recent study that compared direct and derived scores of TMT between adults with hearing loss and normal hearing also demonstrated significant differences (Chandrashekar & Nagaraj, 2024b).

TMT-B is often utilized as a measure of cognitive flexibility or set-shifting, which is a key component of executive attention control (Arbuthnott & Frank, 2000; Horton, 1979; Kortte et al., 2002; Moll et al., 2002). EF such as working memory, inhibition control, or set-switching are more specifically involved in TMT-B performance (Llinas-Regla et al., 2017). This is pertinent to the study of cognitive aging and executive function, especially in the context of the complex differential diagnosis of adults who may exhibit mild executive dysfunction, which is frequently an early sign of a degenerative disorder. Hence, this finding is consistent with that of previous studies. Successful completion of the TMT is believed to depend on several distinct cognitive processes, including EF and fluid intelligence. Therefore, it is crucial to identify which processes predict differences in TMT-B performance.

Cognitive changes are not only linked to declines in executive functions (MacPherson et al., 2002; Mittenberg et al., 1989) but also to other cognitive processes associated with TMT-B performance (Salthouse, 2011a, 2011b). Regression analyses

have shown that tests measuring processing speed and working memory partially mediate the effects on TMT-B performance (Oosterman et al., 2010; Sánchez-Cubillo et al., 2009), as well as episodic memory (Oosterman et al., 2010), verbal ability (Knight et al., 2006), and arithmetic, visuomotor, and visuospatial abilities (Christidi et al., 2015). So, all these processes can affect the outcome of TMT performance which has to be interpreted cautiously. It becomes crucial to investigate each of these components and their shared and independent contributions to TMT-B performance, beyond the influence of general cognitive ability.

Slower processing speed has been linked to longer TMT-B completion times. This connection is not surprising, given the task's requirement to quickly alternate between numbers and letters. Previous research has also demonstrated that individual differences in processing speed are predictive of TMT-B performance (Misdraji & Gass, 2010; Oosterman et al., 2010; Sánchez-Cubillo et al., 2009). Salthouse (2011a) found that a latent speed factor is associated with performance on a variant of TMT-B. This finding suggests that hearing loss may not necessarily impact only the EF but also other cognitive processes measured by the TMT-B, highlighting the need for further investigation into the relationship between hearing loss and cognitive function.

5.3 Performance on the Stroop task in terms of accuracy and reaction time between AHL and NTA

The third objective of the study was to compare the performance of the Stroop task in terms of accuracy and reaction time (RT) between AHL and NTA groups. Accuracy was measured for all the conditions combined and RT was measured as average RT, RT for congruent and incongruent conditions, and Stroop effect. Significant differences were found for average RT and RT in both congruent and

incongruent conditions but not in the Stroop effect. The Stroop task was considered in the present study to study the inhibitory control in the AHL and NTA groups. The primary goal of the Stroop Color-Word Test (Stroop, 1935) is to inhibit a well-practiced response in favor of a less familiar one (Strauss et al., 2006).

There are various versions of the Stroop task, but the current study involved displaying words on a screen in different font colors, with instructions to respond to the font color rather than the word's meaning. In congruent trials, where the font color matches the word's meaning (e.g., "BLUE" in blue font), responses are faster and errors are fewer compared to incongruent trials, where the font color and word meaning differ (e.g., "BLUE" in red font). The average difference in performance between congruent and incongruent trials is commonly known as the Stroop effect (MacLeod, 1991). When the color and word are congruent, the task is straightforward; however, when they are incongruent, participants experience interference, making the task more challenging (MacLeod, 1991; Stroop, 1935). Even in the present study, similar results were found where participants in both groups performed better in congruent conditions.

However, in a conflictual situation, such as overcoming a habitual action in favor of an unusual one, at least three cognitive operations are required. First, the mind must detect interference between two parallel processes. Second, it must make a decision by focusing on goal-relevant information while simultaneously inhibiting irrelevant information. Finally, it must suppress the habitual action and generate an appropriate response based on the decision made. These complex mental operations are collectively referred to as "interference resolution." This type of operation can be attributed to the executive network of attention or EF, which is responsible for managing complex cognitive tasks such as interference resolution. The Stroop interference effect shows that reaction times are consistently longer in incongruent

trials compared to congruent ones (MacLeod, 1991). The executive attention network is involved in detecting conflicts, making decisions to prioritize relevant information, and inhibiting automatic or habitual responses to achieve goal-directed behavior (Petersen & Posner, 2012; Posner, 2008, 2012). Consequently, participants in the present study performed poorer in incongruent conditions.

The interference in the Stroop task arises from the conflict between the automatic process of word reading and the more effortful process of color naming (Augustinova & Ferrand, 2014; Cohen et al., 1990; Luo, 1999; Schneider & Chein, 2003). This "Stroop interference or effect" reflects the ability to inhibit a habitual, overlearned response in favor of a less familiar one (Homack & Riccio, 2004). Concerning the Stroop effect, researchers have proposed several theoretical explanations (Aron, 2007). A widely accepted explanation is that our natural inclination to read visually presented words is much stronger than our tendency to name colors, which is less automatic. As a result, the instinct to read the word should be suppressed and instead focus on naming the font color, a task that becomes particularly challenging in incongruent trials (Cohen et al., 1990; MacLeod, 1991). Despite extensive research, it remains unclear whether the Stroop effect originates at the task set level, semantic level, or response selection level (Parris et al., 2019). Additionally, some studies suggest that separate neural processes may be involved in detecting and resolving conflict during Stroop tasks (West, 2003). Research has also shown that Stroop task performance can be influenced by contextual factors, such as circadian rhythm (Ramlrez et al., 2012) and practice (Davidson et al., 2003), as well as individual differences like age (West, 1999).

Luo (1999) explained that while color naming requires the activation of a specific network within the verbal-lexical system, word reading only necessitates the

activation of the relevant network in the lexical-verbal system, making the use of the semantic system optional. The primary cognitive challenge for participants in the Stroop task and similar versions is to "ignore or override" the semantic codes of the verbal-lexical system in order to respond correctly. If a participant fails to override this automatic response, they will either take longer to respond or fail to select a response. This cognitive monitoring and inhibition of the verbal-lexical system is referred to as "response override" (Botvinick et al., 2001). The increased RT in the Stroop task primarily reflects the process of semantic processing, specifically when the concept represented by the color word and the color of the ink are incongruent. This suggests that effortful trials reveal the subject's ability to detect semantic interference. Proponents of the semantic explanation argue that interference occurs during early processing, related to semantic encoding before a response is made. Both the color to be named and the word to be ignored trigger similar semantic codes, leading to competition between these two dimensions before the response output (Green et al., 2016).

Several studies have shown that older adults exhibit a larger Stroop effect compared to younger adults (Anstey et al., 2000; Cohn et al., 1984; Comalli et al., 1962; Rogers & Fisk, 1991). While some researchers attribute this difference to age-related declines in processing speed (Salthouse & Meinz, 1995), others argue that it reflects age-related deficits in inhibition (Hasher & Zacks, 1988). These deficits persist even after accounting for processing speed (Spieler et al., 1996) and may be linked to age-related changes in frontal neural circuitry (West, 1996) and overall neurobiological functioning (Braver & Barch, 2002). All the factors mentioned above likely played a role in the results observed in this study.

A study found that responding to the font color instead of the lexical content in incongruent trials is challenging, a report often echoed by both young and older adult participants. However, some participants from both age groups have reported finding the Stroop task easy. When asked to elaborate, they mentioned using strategies like relying on peripheral vision, focusing only on the final letter, or deliberately blurring their vision. These tactics likely help reduce the processing of the lexical content, thereby minimizing the need to inhibit this information (Ward et al., 2021). This suggests that the strategies participants use to perform the task can vary significantly, depending on the individual and their approach to problem-solving. This variability in methods could also have influenced the results observed in the present study.

Recent neuroimaging studies have identified a cortical network that is activated when inhibition is required, involving the prefrontal, parietal, temporal, and cingulate areas (Bush, 2011; Collette et al., 2006). These areas are similar to those involved in top-down attentional control, including the anterior cingulate cortex, the intraparietal sulcus, and the dorsolateral prefrontal cortex (Aron, 2007; Mansouri et al., 2009; Wang et al., 2010). Several neuroimaging studies have shown increased activation in cortical areas such as the dorsolateral prefrontal cortex, anterior cingulate cortex, and posterior parietal cortex (Bush et al., 1998; Chen et al., 2013; Pardo et al., 1990). This evidence supports the connection between the Stroop test, inhibition, and attentional control. Various brain regions, including the superior frontal gyrus and inferior frontal gyrus, are strongly activated during the incongruent trials. It was observed that the prefrontal cortex, particularly the cingulate gyrus, supramarginal gyrus, and inferior frontal gyrus, were more responsive to the incongruent effect, while these areas showed no activation during congruent trials (Jalalvandi et al., 2020). It was also found that the prefrontal region plays a crucial role in cognitive processes during both congruent and incongruent

trials. Findings from previous studies have consistently demonstrated that the prefrontal cortex is essential for cognitive control, and it may be particularly involved in managing conflict processes (Brass et al., 2003; Derrfuss et al., 2005; MacDonald et al., 2000).

However, incorporating the Stroop test to differentiate between hearing loss and normal hearing groups has been scarcely explored. A recent study that investigated the impact of hearing loss on cognitive function in individuals with subjective cognitive decline revealed that individuals with hearing loss performed worse on the Stroop Color Word Test, indicating deficits in frontal executive function, compared to those with normal hearing (Park et al., 2022). Another study that compared inhibitory control between adults with and without hearing loss also found a significant difference in the Stroop effect (Shende et al., 2021). Hence, it can be concluded that inhibitory control is likely affected in the AHL group. The observed differences in cognitive performance between the hearing loss group and the normal hearing group suggest that hearing loss may have an impact on the ability to inhibit automatic responses.

5.4 Performance on the Go/NoGo task in terms of accuracy and reaction time between AHL and NTA

The fourth objective of the study was to compare the performance of the Go/NoGo task in terms of accuracy and RT between AHL and NTA groups. Significant differences were obtained for RT and not for accuracy in the present study. The Go/NoGo task involves both the execution and suppression of motor responses, highlighting aspects of executive control. Specifically, the association or binding between stimulus features and responses facilitates the execution of Go processing (Hommel & Bernhard, 1998), which converts sensory information into motor behavior. In contrast, NoGo processing requires the suppression of motor responses (Adelhöfer

et al., 2019; Asci et al., 2019; Liddle et al., 2001). Inhibition is a crucial aspect of EF, referring to the ability to suppress dominant or automatic responses when needed (Logan, 1994; Miyake et al., 2000).

Numerous studies have demonstrated that the neural networks associated with executive control in the Go/NoGo task include regions such as the dorsolateral prefrontal cortex, ventrolateral prefrontal cortex, supplementary motor area, posterior parietal cortex, inferior parietal lobule, insula, and superior temporal gyrus (Nakata et al., 2008; Xiao et al., 2021). Although Go/NoGo tasks have been extensively used in studies involving normal cognitive aging and various clinical populations, they have rarely been applied in the context of hearing loss, except the study by Shende et al. (2021). The hearing loss group in their study exhibited greater difficulty inhibiting their pre-potent responses during the infrequent NoGo trials compared to the normal hearing group. This difficulty resulted in higher error rates, such as false alarms, suggesting deficits in inhibitory control. However, in the present study, significant differences were obtained only for the RT, still suggesting reduced inhibitory control in the AHL group. Overall, the current findings related to inhibition suggest that cognitive alterations in inhibitory control seem to manifest even in individuals with milder degrees of hearing loss.

The possible reasons for obtaining the results in the present study are discussed further. An increasing body of evidence suggests a connection between ARHL and cognitive decline, yet the nature of their relationship remains elusive. Determining whether one condition causes the other, or if they share a common underlying factor, holds significant implications for prevention, rehabilitation, and health policy. However, establishing a causal relationship in natural, correlational samples poses

challenges, particularly as hearing and cognition are complex to measure independently. In a critical review (Wayne & Johnsrude, 2015) of the evidence regarding the link between hearing loss and cognitive decline, several hypotheses proposed to explain this link were explored, ultimately concluding that no single hypothesis adequately explains the relationship. Numerous studies have delved into the intricate relationship between hearing loss and cognitive decline, yet the precise mechanisms and causal links remain incompletely understood, giving rise to various hypotheses including the cognitive load hypothesis, common cause hypothesis, cascade hypothesis, and overdiagnosis or harbinger hypothesis (Uchida et al., 2019).

A study analyzed cross-sectional data from 66-year-old participants who completed the Korea National Health and Nutrition Examination Surveys and assessed their auditory function through pure-tone audiometric testing and cognitive disorder with memory dysfunction was evaluated using standardized scores from the Prescreening Korean Dementia Screening Questionnaire. The findings revealed that bilateral hearing loss was associated with a higher prevalence of cognitive disorder with memory dysfunction compared to unilateral hearing loss or normal hearing. After adjusting for various factors, including demographics and health conditions, individuals with bilateral hearing loss exhibited a higher risk of cognitive disorder with memory dysfunction than those with unilateral hearing loss or normal hearing. These results underscore the significant impact of hearing loss on cognitive function with bilateral hearing loss particularly associated with poorer cognitive outcomes (Lee et al., 2021). A similar situation could have occurred in the present study, where significant differences between the two groups might be attributed to the inclusion of participants with bilateral hearing loss.

Utilizing a sample of 160 adults enrolled in Program for All-inclusive Care for the Elderly programs in Massachusetts and Rhode Island, the researchers found a high prevalence of hearing loss and cognitive impairment among the participants, with 43% exhibiting at least mild hearing loss in the better hearing ear in addition to cognitive impairment (Mamo & Wheeler, 2021). This supports the findings of the present study, where cognitive changes were observed even in participants with mild hearing loss (Babajanian & Gurgel, 2022).

A cross-sectional study encompassing two US epidemiologic datasets, namely the Hispanic Community Health Study (HCHS) and the National Health and Nutrition Examination Study (NHANES), that explored the association between hearing and cognition among 6451 participants aged 50 years or older, revealed decreased scores across all cognitive tests (Golub et al., 2020). Further, Liu & Lee (2019) demonstrated that individuals aged 45 to 64 years with hearing loss had a particularly elevated risk of dementia. A recent study found that the prevalence of cognitive impairment in the 50+ population was found to be 9.3%. Individuals with any level of hearing loss were significantly more likely to experience cognitive impairment (Tambley et al., 2023). This indicates that cognitive changes can start as early as midlife, as demonstrated in the current study.

On the contrary, Croll et al. (2021) studied the relationship between hearing loss and cognitive decline study involving 3,590 non-demented participants. At baseline, hearing loss was associated with lower cognitive function, and over a follow-up period of approximately 4.4 years, it was linked to an accelerated decline in memory test performance. However, upon further adjustment for the interaction between age and follow-up time, the association between hearing loss and accelerated cognitive decline

became non-significant. This suggests that the effects of hearing loss on cognitive decline may not extend beyond the natural age-related declines in cognitive function. However, the results obtained in the present cross-sectional study do not align with this perspective. Since the current participants were assessed at a single time point, longitudinal follow-up would be necessary to accurately determine whether hearing loss contributes to accelerated cognitive decline beyond normal aging.

Another possible reason could be the participants' childhood cognitive abilities, which may have influenced their cognitive performance later in life. These early abilities could have contributed to the differences observed between the groups in the study. A study investigated the potential role of childhood cognitive ability in the relationship between hearing impairment and cognitive function in later life utilizing data from the Lothian Birth Cohort, 1936. The authors suggested that childhood cognitive ability may contribute to the association between hearing impairment and cognitive function in later life (Okely et al., 2019). These findings underscore the potential importance of early-life cognitive ability in understanding the relationship between hearing impairment and cognitive function across the lifespan. This holds importance for another reason, education is considered a modifiable risk factor for developing dementia in later life. Higher levels of education in early life have been linked to a lower risk of cognitive decline (Livingston et al., 2020), making it a critical factor in understanding and potentially mitigating the onset of dementia.

In this context, it becomes essential to consider not only early-life cognitive ability and educational attainment as protective factors but also the specific cognitive domains that may be differentially affected by hearing loss. Understanding the neural underpinnings of functions like cognitive flexibility and inhibitory control can shed

light on how hearing impairment might intersect with these processes, potentially influencing cognitive outcomes across the lifespan.

The neural circuitry and neurocognitive processes underlying cognitive flexibility and inhibitory control involve key brain regions and neurotransmitter systems. The prefrontal cortex (PFC), particularly the dorsolateral PFC, is integral to cognitive flexibility, facilitating set-shifting and working memory updates, while the ventrolateral PFC supports inhibitory control through response inhibition. The anterior cingulate cortex (ACC) plays a crucial role in conflict monitoring and error detection, ensuring adaptive behavior. The basal ganglia, especially the striatum, interact with the thalamus and PFC to regulate action selection and suppression of prepotent responses. The parietal cortex aids in attentional shifts necessary for cognitive flexibility. Neurochemically, dopamine modulates task-switching and inhibitory processes via the cortico-striatal-thalamic loop. Noradrenaline from the locus coeruleus enhances attentional control, while serotonin influences impulse regulation and emotional aspects of inhibition. Glutamatergic signaling supports synaptic plasticity required for flexible thinking, and GABAergic inhibition fine-tunes response suppression. Collectively, these neural circuits and neurotransmitters orchestrate the balance between adapting to new information and suppressing inappropriate responses, ensuring goal-directed behaviour (Logue & Gould, 2014). These findings suggest that certain cognitive processes may be influenced by hearing loss; however, the extent and nature of these effects remain uncertain and warrant further investigation.

5.5 Correlation between outcome measures of verbal fluency, TMT-B, Stroop task and Go/NoGo task

The fifth objective of the study was to study the correlation between outcome measures of verbal fluency, TMT-B, Stroop task and Go/NoGo task. Significant correlations between outcome measures were observed only for few pairs for AHL and NTA groups. The pattern of significant correlations among outcome measures in the AHL group suggests interrelated deficits across semantic, phonological, and executive functioning domains in individuals with hearing loss. Specifically, the significant positive correlations between fluency tasks—such as Fruits Accuracy (FA), Colors Accuracy (CA), and Phoneme /p/ Accuracy (PA)—highlight the potential overlap in the cognitive-linguistic mechanisms required for word retrieval, including lexical access and semantic organization. These associations reflect a shared reliance on semantic memory and executive control, processes known to be susceptible to degradation in the presence of hearing loss.

The strong correlation between NA (Phoneme /n/ Accuracy) and PA ($r = .744$, $p < .01$) may indicate consistent phonological fluency performance across different stimuli, possibly due to similar phonemic processing demands. Additionally, correlations between CA and alternate fluency tasks (AF2 and AF3) suggest that performance in semantic-based tasks is predictive of performance in more complex, cognitively demanding switching tasks. This is likely because both task types depend on executive control processes such as cognitive flexibility, attention shifting, and inhibitory control.

Furthermore, significant negative correlations between fluency tasks and executive function measures—such as AF2 with SART ($r = –.509$) and Stroop measures

with AF3 and Go/NoGo Reaction Time—highlight the interdependence between language and executive function. These results imply that poorer inhibitory control and longer reaction times may be linked to reduced fluency performance, reinforcing the notion that hearing loss may exacerbate cognitive strain during verbal tasks.

The associations between Stroop task components (SCRT, SIRT, SE) and fluency outcomes further underscore the role of attentional control and conflict monitoring in successful word retrieval. The negative correlations with the Stroop Effect (SE) and GNRT (Go/NoGo Reaction Time) reflect that increased cognitive interference and slower processing speed may adversely impact verbal output.

Collectively, these results align with existing literature suggesting that hearing loss not only affects auditory perception but also contributes to broader cognitive inefficiencies. The observed correlations highlight the integrative nature of language and executive processes and point to the potential for cognitive decline to be exacerbated by auditory degradation in the aging population.

In the NTA group, the observed significant correlations primarily reflect the typical cognitive-linguistic integration expected in individuals with normal hearing. The positive correlations among semantic and phonemic fluency tasks (e.g., CA–NA, CA–PA, NA–AF(2), PA–AF(2)) suggest that lexical retrieval abilities across different domains—semantic (e.g., colors, fruits) and phonemic (/p/, /n/)—are closely linked. These results highlight the efficiency of intact semantic memory networks and phonological processing systems in supporting word generation under various task demands.

The strong correlation between AF(2) and AF(3) (r = .630, $p < .001$) further emphasizes the consistency in performance across alternate fluency tasks, both of which require cognitive flexibility to shift between semantic and phonemic rules. This suggests that individuals with normal auditory function may engage executive processes more fluidly during complex verbal tasks, maintaining high accuracy across conditions.

Moreover, the robust correlation between Stroop Congruent (SCRT) and Incongruent (SIRT) Reaction Times (r = .935, $p < .001$) demonstrates a stable and efficient response system for managing cognitive interference and attentional control. The correlation between SIRT and GNRT (r = .458, $p = .04$) also indicates shared reliance on inhibitory control and processing speed across both executive functioning measures.

Unlike the AHL group, where hearing loss may place added cognitive load and disrupt typical processing patterns, the NTA group shows a more cohesive pattern of inter-domain relationships. These findings underscore the role of intact auditory input in supporting seamless integration of language and executive functions, facilitating efficient task performance with minimal cognitive strain.

A comparative discussion summarizing key differences and similarities between the AHL and NTA groups based on the correlation findings are explained further. The correlation patterns observed in the AHL and NTA groups reveal distinct profiles in how cognitive-linguistic processes interact, likely influenced by the presence or absence of hearing loss.

Breadth of Correlations: The AHL group demonstrated a broader range of significant correlations across semantic fluency, phonemic fluency, alternate fluency, and executive functioning measures. This may indicate increased interdependence or compensatory engagement of cognitive resources due to hearing-related processing deficits. In contrast, the NTA group showed fewer but more focused correlations, primarily within related domains (e.g., between fluency types or among executive function tasks), suggesting more domain-specific and efficient processing.

Integration Across Domains: In the AHL group, correlations between fluency tasks and executive function measures (e.g., Stroop and Go/NoGo tasks) suggest that hearing loss might contribute to a higher cognitive load, forcing greater reliance on executive functions during language tasks. This reflects a more diffuse engagement of cognitive systems. In the NTA group, significant correlations were largely restricted within fluency tasks or within executive function tasks, indicating more specialized, efficient system functioning with less cross-domain dependency.

Fluency Task Relationships: Both groups showed significant positive correlations between different fluency task types (e.g., semantic–phonemic, phonemic–alternate), highlighting the shared linguistic and cognitive bases of word generation. However, the AHL group exhibited stronger cross-links, suggesting reduced modularity in processing and possible overlap due to compromised auditory and linguistic input.

Executive Function Measures: While both groups showed significant correlations between Stroop Congruent and Incongruent Reaction Times, only the AHL group showed correlations between fluency and executive function performance (e.g., Stroop Effect, Go/NoGo RT). This pattern suggests that individuals with hearing loss

may require greater executive involvement to compensate for difficulties in automatic linguistic processing.

Overall, the findings suggest that hearing loss alters the cognitive-linguistic architecture, increasing reliance on executive control and reducing the independence of functional domains. In contrast, normal-hearing individuals exhibit more domain-specific efficiency, with cognitive and linguistic tasks functioning more autonomously.

5.6 Association between groups and health & lifestyle related factors

The sixth objective was to investigate the association between groups and health & lifestyle related factors. No significant association was found between the groups (AHL and NTA) and any health & lifestyle related factors, including hypertension, diabetes, smoking, alcohol consumption, and physical exercise. This suggests that these factors were comparably distributed across both groups and likely did not contribute to the observed differences in outcomes.

Although previous literature has often highlighted the influence of comorbid health conditions and lifestyle habits on cognitive aging and hearing health (Genther et al., 2015; Mener et al., 2013; Shargorodsky et al., 2010), the absence of significant associations in the current study may be attributed to several factors. First, the sample size might limit the statistical power, making it challenging to detect meaningful differences even if subtle effects exist. This limitation increases the risk of Type II error, where existing effects are not identified due to a lack of power. Health-related data—such as levels of physical activity, smoking, or alcohol consumption—were collected through self-report, it may have introduced inaccuracies, thereby potentially attenuating the strength of the observed associations. Additionally, the interplay between these

health conditions can be complex, potentially diluting each factor's individual impact on the groups. For example, certain combinations of these factors, such as hypertension coupled with diabetes, might interact in unique ways, potentially mitigating or amplifying their impact on the groups. Furthermore, adults with hearing loss may have developed compensatory cognitive strategies over time, which could help maintain cognitive flexibility and inhibitory control despite the added cognitive burdens associated with health factors. This adaptive capacity might mask the negative effects of these conditions, making them less apparent.

Variability in disease severity and duration is another important consideration. For instance, participants with mild or well-controlled conditions may experience less cognitive impact compared to those with severe or poorly managed health issues, blurring group-level effects. Additionally, cumulative effects of conditions like hypertension and diabetes might take longer to manifest. Therefore, since the study included middle-aged adults or individuals with relatively shorter durations of the condition, the complete cognitive effects may not yet be observable.

The unique characteristics of the hearing loss population may also play a role. Adults with hearing loss often develop resilience through lifestyle adaptations, possibly engaging in cognitive and social activities differently from the general population, which could mitigate the impacts of other health factors. Furthermore, variables such as age, education, and cognitive reserve may serve as moderators, potentially enhancing resilience and masking the effects of hypertension, diabetes, and lifestyle factors. In summary, the lack of significant findings may be due to a combination of sample size limitations, measurement sensitivity, complex health factor interactions, and the unique adaptations within the hearing loss population.

Moving forward, it was previously found that greater hearing loss was significantly associated with lower measures of EF suggesting an independent association between hearing loss and lower EF scores, ascertaining that hearing loss serves as an early indicator of cognitive decline (Bush et al., 2015; Diao et al., 2019; Lin, 2011, Lin et al., 2013). Hence, it is essential to identify novel measures that can predict individual hearing and cognitive abilities, while also addressing individual risk components (Paglialonga et al. 2023). The present study aims to achieve similar objectives by incorporating the tasks discussed above to explore cognitive changes in individuals with hearing loss. There appears to be a connection between hearing loss and executive functions, where reduced sensory input may lead to decreased cognitive stimulation, potentially causing poorer cognitive performance in individuals with hearing loss (Brannstrom et al., 2020).

From a neuroanatomical perspective, hearing impairment has been consistently linked with accelerated cognitive decline and incident dementia in longitudinal studies, as well as with reduced volumes in the auditory cortex in cross-sectional studies. Individuals with hearing impairment exhibited accelerated volume declines in both whole brain and regional volumes, particularly in the right temporal lobe (including the superior, middle, and inferior temporal gyri, as well as the parahippocampus) (Lin et al., 2014).

In a recent cross-sectional study, the alterations in the thalamus and its subdivisions were investigated in individuals with sensorineural hearing loss (SNHL) compared to normal participants. SNHL patients exhibited decreased fractional amplitude of low-frequency fluctuation, indicating reduced thalamic activity. Moreover, SNHL was associated with weakened thalamic connectivity with various

brain regions, including the cerebellum, cingulate cortex, insula, and temporal gyrus. These functional connectivity abnormalities correlated positively with cognitive test scores and demonstrated high discriminative power between SNHL patients and normal participants. Overall, the findings suggested that SNHL induces widespread alterations in thalamic function and connectivity, potentially contributing to cognitive impairments associated with hearing loss (Xu et al., 2019).

Although cognitive flexibility is known to be associated with the frontal lobes, it may involve other brain regions as well. For instance, findings from an event-related potential (ERP) study suggest that the process of cognitive flexibility activates not only the frontal regions but also the bi-occipital and parietal regions (Moulden et al., 1998). It is conceivable to assume that the more advanced neuropathology of AD alters the relationship among cognitive mechanisms, thereby contributing to differences in the structure of executive control (Brandt et al., 2009) affecting the performance of EF tasks.

The auditory and cognitive functioning not only decline in parallel but also mutually influence each other's trajectories over time (Ghisletta et al., 2023). Recent studies have found that older adults with hearing loss were 2.66 times more likely to experience cognitive impairment compared to those without hearing loss, indicating a significant association between the two conditions. These findings underscore the importance of early identification of hearing loss and cognitive impairment, as both represent modifiable risk factors for healthy aging and may be amenable to preventive or therapeutic interventions (Deal et al., 2017; Ge et al., 2021; Lau et al., 2022; Paiva et al., 2023, Soons et al., 2024).

To summarize, after synthesizing data from 40 studies across 12 countries involving approximately 20,264 participants a meta-analysis revealed a significant association between ARHL and various domains of cognitive function (Loughrey et al., 2018). Overall, ARHL emerges as a possible biomarker and modifiable risk factor for cognitive impairment and dementia (Conceição Santos de Oliveira et al., 2023; Fu et al., 2022; Taljaard et al., 2016). The most recent study in this area reported incident hearing loss was associated with an accelerated decline in verbal memory, information processing speed, and executive function (Soons et al., 2024). Notably, the onset of hearing loss preceded the onset of cognitive decline, highlighting hearing loss as a potential risk factor independent of other dementia risk factors.

Studies have also shown that hearing loss is linked not only to cognitive decline but also to depression (Barbosa et al., 2023; Powell et al., 2022; Sharma et al., 2021), which is itself a risk factor for developing dementia. Associated health issues include dependency on activities for daily living (Liu et al., 2022), impaired balance leading to falls, increased hospitalizations, early mortality, and perception of handicap (Chang et al., 2009). Socially, hearing loss can result in reduced communication function, social isolation, loss of autonomy, compromised driving ability, and financial decline (Davis et al., 2016). This creates a complex interplay of conditions, further increasing the risk for dementia.

This underscores the importance of addressing hearing loss through interventions such as hearing aids and rehabilitative services, particularly in the early stages of aging, to potentially mitigate cognitive decline (Tamblay et al., 2023). Interestingly, those with hearing loss who reported using hearing aids had a lower risk of cognitive impairment compared to non-users (Tognola et al., 2019). Restoring

hearing can alleviate cognitive load, thereby enhancing cognitive performance (Martini et al., 2014). Studies have shown an increase in cognitive scores post aural rehabilitation highlighting the importance of hearing loss treatments (Utoomprurkporn et al., 2020).

Integrating cognitive assessments into hearing evaluations, and vice versa is crucial but has not been implemented effectively in practice. Studies have shown that a majority of professionals in memory services estimated that over 25% of their patients had significant hearing difficulties, and most found it useful to inquire about hearing difficulties. However, only a small percentage performed hearing tests in the clinic. Conversely, a significant portion of audiologists estimated that over 25% of their older adult patients had significant memory problems, and most found it useful to perform cognitive assessments, but only a few actually did so. The main barriers cited included lack of training, time, and resources (Omar et al., 2023). The only study available to date that assessed dementia knowledge among upcoming speech-language pathologists in the Indian scenario also indicated that their understanding of the condition is limited (Chandrashekar & Nagaraj, 2024a). These findings underscore the need for improved education and integration of cognitive and audiology services and highlight areas for future research and operational solutions to address this comorbidity effectively.

Chapter 6

Summary and Conclusion

Age-Related Hearing Loss (ARHL) is one of the most common sensory impairments associated with aging. It usually manifests as a bilateral, symmetrical sensorineural hearing loss, predominantly affecting high-frequency sounds. Its onset often begins in the fourth decade of life, and it becomes more pronounced with age. ARHL is influenced by a mix of genetic, environmental, and lifestyle factors. Notably, this type of hearing loss is more than just a sensory issue—it has strong connections to cognitive and psychological health. Research shows that hearing loss is not an isolated condition. It significantly impacts mental well-being, contributing to social isolation, depression, and cognitive decline, and is now recognized as a potential modifiable risk factor for dementia, including Alzheimer's disease. The Global Burden of Disease Study (2015) ranks hearing loss as the fifth leading cause of years lived with disability. As global populations age, the prevalence and consequences of hearing loss are expected to increase substantially.

The World Health Organization (WHO) classifies middle age as 44 to 60 years, a stage where early symptoms of ARHL often begin. Yet, research in this demographic is scarce. Studies have largely focused on older adults, despite evidence that early detection and intervention in midlife may be more effective in delaying or preventing dementia. For instance, midlife hearing loss has been linked to late-life brain atrophy, especially in the temporal lobe, which is crucial for auditory and memory functions.

According to Livingston et al. (2020), hearing loss in midlife contributes the highest Population Attributable Fraction (PAF) to dementia risk—up to 8%. This highlights an urgent need to address hearing loss as a public health priority, especially

in low- and middle-income countries (LMICs) like India, where the estimated PAF is 41%, indicating a significant potential for prevention.

Cognition in aging is best understood as a continuum—from healthy aging through mild cognitive impairment to dementia. At the core of cognitive aging are Executive Functions (EF), which include working memory, cognitive flexibility, and inhibitory control. These functions are essential for complex decision-making, task-switching, and suppressing irrelevant responses. Declines in EF often precede more obvious signs of cognitive impairment and are critical in predicting the onset of dementia.

This study focuses on cognitive flexibility and inhibitory control—two components of EF that are especially sensitive to early changes. While working memory has been widely researched and tends to remain intact in early stages of cognitive decline, these other two aspects are more vulnerable and less explored in midlife populations. The research examines adults aged 45 to 55 years with bilateral mild sensorineural hearing loss. Mild hearing loss (defined as a pure-tone average between 25–40 dB HL) has been associated with early cognitive changes, and bilateral loss in particular has shown stronger links with cognitive impairment compared to unilateral loss.

To assess cognitive functioning, the current study used Verbal fluency tasks (semantic, phonemic, and alternating categories) and Trail Making Test-B for cognitive flexibility. Stroop Task and Go/NoGo Task for inhibitory control. These tools are well-established in measuring EF, especially under conditions that require individuals to suppress automatic responses and switch between different cognitive sets. Performance is evaluated in terms of accuracy, reaction time, and completion time, offering insight into early cognitive strain.

The aim of the study was to assess differences in cognitive flexibility and inhibitory control between adults with bilateral mild sensorineural hearing loss and those with normal hearing. The objectives involve comparing performances on multiple EF tests and identifying relationships among various cognitive, health, and lifestyle factors.

A standard group comparison design was used, involving two groups: a clinical group (n = 19) with bilateral mild sensorineural hearing loss and a normal group (n = 21) with bilateral normal hearing sensitivity. The groups were matched for age, education, and socioeconomic background. Further, the participants were selected using purposive sampling, with sample size estimated through G*Power analysis to achieve sufficient statistical power. All individuals were right-handed native Kannada speakers with over 12 years of education, and free from significant neurological, psychiatric, or otological conditions. Cognitive screening was performed using the Montreal Cognitive Assessment (MoCA), and only those scoring above 26 were included. Participants in the clinical group had bilateral mild sensorineural hearing loss, confirmed through pure-tone audiometry and defined as hearing thresholds between 25–40 dB HL. The normal group had thresholds within ≤15 dB HL. All individuals underwent speech audiometry, tympanometry, and acoustic reflex testing to rule out middle ear dysfunction and confirm peripheral hearing status.

All audiological and cognitive assessments were conducted in controlled, sound-treated rooms. Pure-tone audiometry was performed using Inventis Piano audiometer, and immittance testing was done using GSI Tympstar. The Stroop and Go/NoGo tasks were programmed in PsyToolkit and run on a MacBook Pro. A custom response pad was used for obtaining responses from the participants.

The study was carried out in two phases: Phase I – Pre-data collection and Phase II – Data collection and analyses.

Phase I involved:

- Obtaining informed consent.
- Collecting demographic and health-related information.
- Screening for cognitive functioning using MoCA.
- ENT evaluation.
- Audiological testing to confirm group classification.
- Programming and testing the cognitive task stimuli.

Phase II included the administration of cognitive tasks to assess executive functions. Each participant completed the tasks in the same order.

In the present study, four cognitive tasks were employed to assess cognitive flexibility and inhibitory control in adults with and without hearing loss. These tasks included the Verbal Fluency Tasks**,** Trail Making Test–B (TMT-B)**,** Stroop Task**,** and Go/NoGo Task**.** All tasks were administered in a quiet, distraction-free environment with clear instructions provided to the participants. Each task was chosen for its ability to capture specific aspects of executive functioning, and the order of task presentation was kept constant across all participants to ensure consistency.

The Verbal Fluency Tasks were designed to assess cognitive flexibility through word generation under three categories: semantic fluency, phonemic fluency, and

alternating fluency. Each participant completed seven tasks in total—two semantic, two phonemic, and three alternating fluency tasks. For the semantic fluency tasks, participants were asked to name as many items as possible within a specific category (fruits and colors) in 60 seconds. In phonemic fluency, participants had to generate words beginning with the phonemes /n/ and /p/. The alternating fluency tasks were more complex and required switching between two semantic categories (animals and vegetables), two phonemes (/r/ and /s/), and a semantic category and a phoneme (common objects and /k/). Participants were instructed to avoid repetitions, proper nouns, or word variations. The responses were audio-recorded and later scored manually, with one point awarded for each correct word in semantic and phonemic tasks and for each correct alternation in the alternating fluency tasks.

The Trail Making Test–B (TMT-B) was used to measure participants' cognitive flexibility and task-switching ability. Participants were presented with a printed sheet containing randomly arranged numbers and letters, each enclosed in circles. They were instructed to draw lines to connect the circles in an alternating numeric and alphabetic sequence (e.g., 1-A-2-B-3-C, and so on) as quickly and accurately as possible. A stopwatch was used to record the total time taken to complete the task. Immediate corrective feedback was provided in case of any sequencing errors. The task was discontinued if it could not be completed within 300 seconds. The primary outcome measure was the time to completion, which was used to indicate cognitive flexibility.

To assess inhibitory control**,** the Stroop Task was administered using PsyToolkit software on a MacBook Pro laptop. Participants were shown color words (e.g., "blue," "red," "green," "yellow") that appeared in either congruent (matching ink color and word) or incongruent (non-matching ink and word) formats. They were instructed to

respond based on the ink color alone, disregarding the word itself, by pressing the initial letter of the ink color on a custom response pad (Y for yellow, G for green, R for red, and B for blue). Each stimulus appeared on the screen for 5000 milliseconds with an inter-stimulus interval of 1000 milliseconds. A total of 45 trials were administered, including 5 practice trials, 20 congruent, and 20 incongruent trials presented in random order. Both accuracy and reaction times were recorded for each trial. Additionally, the difference in reaction time between incongruent and congruent trials was calculated as the Stroop Effect**.**

Finally, the Go/NoGo Task was employed to measure response inhibition, another component of inhibitory control. This task, also programmed using PsyToolkit, involved the presentation of visual stimuli where participants were required to press the space bar as quickly as possible when a green "Go" stimulus appeared and to withhold their response when a red "NoGo" stimulus appeared. A total of 30 trials were presented, including 5 practice trials. The Go stimuli were displayed for 500 milliseconds, while NoGo stimuli were shown for 2000 milliseconds, with a consistent inter-stimulus interval of 500 milliseconds. Instructions appeared on-screen alongside the stimuli to reinforce the task demands. Both accuracy and reaction times were recorded for each trial. For each correct response, a score of 1 was awarded, and for incorrect responses, a score of 0 was assigned.

The collected data were analyzed using SPSS version 26.0. Normality was assessed using the Shapiro-Wilk test. Depending on distribution, both parametric (MANOVA, t-tests) and non-parametric (Mann-Whitney U test) statistics were used.

- Mann-Whitney U tested group differences in verbal fluency.
- Independent t-tests analyzed differences in TMT-B and Stroop reaction times.
- Mann-Whitney U tests assessed Stroop accuracy and Stroop effect.
- Spearman's correlation examined relationships among cognitive outcomes.
- Chi-square tests assessed associations between group status and health & lifestyle related measures.

In verbal fluency tasks, under semantic fluency, the AHL group performed significantly worse than the NTA group on both categories—fruits and colors. Mann-Whitney U confirmed statistically significant differences with large effect sizes, indicating lower cognitive flexibility in the AHL group. In phonemic fluency, the AHL group again showed significantly lower accuracy on both phonemes (/n/ and /p/). Mann-Whitney U results revealed strong group differences, indicating reduced phonological retrieval in the AHL group. Alternating fluency tasks revealed that the AHL group performed significantly worse in two out of three tasks, but not in the task alternating between semantic categories. Mann-Whitney U results confirmed a significant group effects particularly in Task 2 and Task 3.

In TMT-B, the AHL group had a significantly longer mean completion time (125.13 seconds) compared to the NTA group (65.56 seconds). Independent t-tests revealed a statistically significant difference ($p < 0.01$), with a large effect size (Cohen's $d = 1.80$), indicating reduced cognitive flexibility in AHL participants.

With respect to the Stroop task, the AHL group had significantly lower accuracy ($M = 27.89$) compared to the NTA group ($M = 39.38$). The Mann-Whitney U test

confirmed this difference ($p < 0.01$) with a high effect size ($r = 0.63$). The AHL group also had significantly slower average RT (M = 2257.42 ms) than the NTA group (M = 1578.14 ms). Both congruent and incongruent RTs were significantly longer for the AHL group, and MANOVA confirmed these differences with large effect sizes. However, no significant group difference was found in the Stroop Effect, suggesting both groups experienced similar levels of cognitive interference.

Accuracy in the Go/NoGo task was comparable between groups (AHL = 24.57, NTA = 25), with no significant difference. However, the AHL group had significantly longer RTs (M = 790.84 ms) than the NTA group (M = 560.23 ms), confirmed by t-test ($p < 0.01$) with a large effect size (Cohen's $d = 1.35$). This indicated slower inhibitory responses in the AHL group.

Spearman's correlations revealed significant relationships among several outcome measures within both groups. In the AHL group, phoneme fluency, alternate fluency, and Stroop/GoNoGo RTs were significantly correlated. In the NTA group, several verbal fluency and RT measures also showed strong associations, suggesting coherent executive function patterns within each group. Chi-square tests showed no significant associations between hearing status and health or lifestyle factors such as hypertension, diabetes, alcohol use, smoking, or exercise.

Out of the hypotheses tested, most null hypotheses were rejected, indicating significant differences in EF between AHL and NTA groups:

- Significant differences were found in verbal fluency tasks, TMT-B, and Stroop task accuracy and RT.

- No significant difference was found in Stroop effect and Go/NoGo accuracy, suggesting similar cognitive interference and inhibitory accuracy across groups.

These findings supported growing evidence that ARHL is not only a sensory problem but is also associated with cognitive changes, especially in EF. In the verbal fluency tasks, the AHL group consistently showed poorer accuracy across semantic, phonemic, and alternate fluency conditions compared to the NTA group. This suggested reduced lexical access, semantic memory, and cognitive flexibility in individuals with hearing loss. These results aligned with prior studies indicating that phonemic fluency is particularly sensitive to hearing loss, likely due to impaired phonological processing. In alternate fluency tasks, the AHL group again performed significantly worse, suggesting difficulty in task-switching or extra-dimensional shifting, a key aspect of EF.

The Trail Making Test-B, a measure of cognitive flexibility and processing speed, also revealed significant differences. The AHL group took nearly twice as long as the NTA group to complete the task. This could not be attributed to differences in age or education, as participants were matched on these variables. The findings indicated that hearing loss may compromise the neural efficiency involved in task-switching and visuomotor coordination, possibly due to greater cognitive load or frontal lobe changes associated with hearing impairment.

In the Stroop task, which measures inhibitory control, the AHL group had lower accuracy and longer reaction times than the NTA group. Although both groups experienced interference in incongruent trials, the AHL group showed a greater slowdown, even though the overall Stroop effect was not significantly different. These results suggested that the AHL group struggled more with suppressing automatic

responses, possibly due to increased reliance on executive resources to compensate for sensory input loss.

In the Go/NoGo task, both groups had similar accuracy, but the AHL group had significantly longer reaction times. This again indicated slower processing speed and reduced inhibitory control in the hearing loss group. Together, the Stroop and Go/NoGo findings supported the idea that hearing loss affects response inhibition, even in midlife and in the presence of only mild hearing impairment.

Correlation analysis showed that in the AHL group, various verbal fluency scores were significantly related to Stroop and Go/NoGo measures. This pattern suggested increased interdependence between language and executive functions in those with hearing loss. In contrast, the NTA group showed domain-specific correlations, reflecting more efficient and independent processing. These differences implied that hearing loss may force the brain to allocate more executive resources to support language tasks, possibly due to degraded auditory input.

Interestingly, no significant associations were found between hearing status and health or lifestyle factors such as hypertension, diabetes, smoking, alcohol use, or exercise. This suggested that the cognitive differences observed were more likely related to hearing loss itself, rather than other health conditions. However, it is to be noted that self-reported health data and the sample size may have limited these findings.

The mean scores obtained from tasks used in the study such as Verbal Fluency, TMT-B, Stroop, and Go/NoGo suggest that these measures can be used to differentiate between adults with hearing loss who have preserved cognitive flexibility and inhibitory control and those who may have deficits in these domains. This highlights

the potential of these tasks in assessing cognitive functioning within the hearing loss population. However, the findings of the current study should be interpreted with caution and replication in a larger and more diverse population is necessary to establish their clinical utility and generalizability.

In conclusion, the study demonstrated that even mild hearing loss in midlife could affect cognitive flexibility and inhibitory control. These findings reinforce the need for early screening, interdisciplinary approaches, and awareness among professionals.

6.1 Implications of the study

The findings of this study underscore the impact of hearing loss on key executive functions, particularly cognitive flexibility and inhibitory control. The observed deficits in verbal fluency, Trail Making Test-B, Stroop, and Go/NoGo tasks suggest that adults with hearing loss may experience subtle cognitive challenges beyond auditory processing. These results highlight the need for early cognitive screening in individuals with hearing loss, even in middle age or early stages of the condition.

Moreover, the significant correlations between outcome measures indicate complex interrelationships among language and executive functioning tasks, which may be further disrupted by auditory deprivation. The lack of association with lifestyle or health-related variables suggests that hearing loss itself could be a more central factor in cognitive differences than general health behaviors in this population.

Clinically, these findings emphasize the importance of adopting a holistic approach in audiological rehabilitation, incorporating cognitive assessments and

interventions. From a research perspective, the study supports the inclusion of cognitive metrics in future longitudinal studies on hearing loss and aging to better understand its role in cognitive decline and to inform targeted therapeutic strategies.

Integrating cognitive assessments into hearing evaluations, and vice versa is crucial and must be effectively implemented in practice. This approach ensures comprehensive care, addressing both auditory and cognitive health, and potentially mitigating the compounded risks associated with hearing loss and cognitive decline. Moving forward, it is essential to promote social awareness regarding the importance of maintaining good hearing and advocate for routine hearing screenings. Given the growing evidence of long-term changes in cognitive abilities in individuals with hearing loss, it is worth re-evaluating our standard approach to audiological care for individuals with hearing loss. Identification of preclinical cognitive changes as early as in midlife rather than waiting for later life symptoms to emerge helps in conserving several upcoming decades for adults who are prone to develop cognitive decline in the future.

6.2 Strengths of the study

- The study identified changes in cognitive flexibility and inhibitory control occurring as early as midlife and in individuals with mild hearing loss, highlighting the importance of focusing on early intervention to help prevent further cognitive decline.
- The study utilized a variety of cognitive tasks, such as verbal fluency tests, the Trail Making Test-B, the Stroop test, and the Go/NoGo task. This comprehensive approach allowed for a detailed examination of different aspects

of executive functioning, particularly cognitive flexibility and inhibitory control.

- The engagement of EF is typically deemed robust when the task is novel (Rabbitt, 1997). Consequently, repeated exposures to the task may reduce its efficacy in truly assessing the intended executive process, potentially resulting in reduced reliability. To avoid this, all the tasks were administered on the same day.
- The cognitive tasks employed in this study are novel for the hearing loss population, offering new insights into the cognitive effects of mild hearing loss that have not been explored in this specific group before.
- The study employed audiometric assessments rather than relying on self-reported measures of hearing loss, a methodological choice that could significantly influence the accuracy and reliability of the findings. Self-reported hearing loss is often subject to individual perception and may result in underreporting or overreporting, as individuals may be unaware of or unwilling to acknowledge their hearing difficulties. In contrast, audiometric testing provides objective and quantifiable measures of hearing ability, reducing the potential for bias and ensuring a more precise assessment of the participants' auditory status.
- Given the global aging population and the rising prevalence of dementia, this study is timely and relevant, addressing an urgent need to understand and mitigate modifiable risk factors like hearing loss as early as mid-life.

6.3 Limitations of the study

- It is challenging to assess cognitive flexibility and inhibitory control in isolation using the tasks involved in the present study because their performance also relies on other cognitive abilities. For instance, the TMT, being a visuomotor task, requires motor speed and coordination. The significant reliance on motor skills may limit the effectiveness of these tests in accurately assessing cognitive flexibility. Although the TMT-B is considered an executive test (Delis et al., 2001; Lezak, 1995; Reitan & Wolfson, 1993) there is ongoing debate about the extent to which executive functioning overlaps with other cognitive domains (Cox et al., 2014; Davis et al., 2011; Rabbitt et al., 2001; Salthouse, 2005). Therefore, using the TMT-B score alone as a measure of EF might lead to an overestimation or underestimation of the impact of other cognitive factors. The 'task impurity' problem poses a particularly challenging issue in studies focused on EF (Burgess, 1997; Phillips, 1997). As EF inherently involves the manipulation of other cognitive processes, any task used to assess EF inevitably engages additional cognitive processes that may not be directly pertinent to the specific EF under investigation. Therefore, a low score in a particular EF task does not necessarily mean inefficient or impaired EF (Miyake & Shah, 1999).
- The tasks considered heavily rely on visual input since the stimuli used in the study are mostly visual. However, to gain a comprehensive understanding of the nature of these changes, it is essential to examine cognitive control through both auditory and visual tasks within the same group of participants.

6.4 Future directions

- To thoroughly grasp the changes in cognitive flexibility and inhibition associated with hearing loss, it is essential to use a multi-disciplinary approach. This should involve a blend of behavioral, neuroimaging, and electrophysiological methods, applied in both cross-sectional and longitudinal studies.
- It would be worthwhile to examine all three cognitive control processes—cognitive flexibility, inhibitory control, and working memory updating—in the same group of participants. Such an examination could provide valuable insights into the vulnerability of different cognitive control processes and inform future research in this area.
- Studies can involve various types and degrees of hearing loss across different age groups to facilitate comprehensive comparisons.
- Future research should include a thorough assessment of both peripheral and central auditory functions. Investigating additional central auditory processes could provide further insights into the relationship between hearing and cognitive control.
- Understanding whether and how auditory rehabilitation approaches, such as hearing aids, affect performance on cognitive control tasks in individuals with hearing loss can help guide the development of novel interventions.
- The present study focused solely on individuals with unaided hearing loss. Future research should investigate how using various hearing aids affects cognitive flexibility and inhibition, and whether hearing aids can help alleviate these cognitive changes.

- Furthermore, it is crucial to develop management approaches that proactively support cognitive health and prevent cognitive alterations in individuals with hearing loss, beyond just the standard prescription of hearing aids. Advancing hearing care for adult clients is not only important but also urgent, considering the rising global incidence (Haile et al., 2021) of ARHL and its associated risks (Livingston et al., 2020).
- Involving individuals with dual sensory impairments (both visual and auditory impairments) in future research could provide valuable insights into how these combined sensory deficits impact cognitive processes. This approach could help differentiate the specific cognitive challenges associated with each type of impairment and better understand their cumulative effect on executive functioning, cognitive decline, and overall quality of life.

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APPENDIX A

ETHICS COMMITTEE APPROVAL CERTIFICATE

All India Institute of Speech and Hearing
(An autonomous Institute under the
Ministry of Health and Family Welfare, Govt. of India)
Center of Excellence - Assessed & accredited by NAAC with 'A' Grade
ISO 9001: 2015 Implemented Institute
Manasagangothri, Mysuru - 570 006

ಅಖಿಲ ಭಾರತ ವಾಕ್ ಶ್ರವಣ ಸಂಸ್ಥೆ
ಮಾನಸಗಂಗೋತ್ರಿ, ಮೈಸೂರು - 570 006
अखिल भारतीय वाक् श्रवण संस्थान
मानसगंगोत्री, मैसूरु - 570 006

ETHICS COMMITTEE APPROVAL FOR BIO-BEHAVIOURAL RESEARCH PROJECTS INVOLVING HUMAN SUBJECTS AT AIISH

AIISH ETHICS Committee (AEC)

Title of the Thesis	: Cognitive flexibility and inhibitory control in adults with hearing loss
Name of the Candidate	: Ms. Pooja C
Name of the Guide	: Dr. Hema N
Name of the Co-Guide	: Nil
Proposed Duration of the Research Study	: 3 to 6 years
Source of funding	: Nil
Estimated budget	: Nil
Reference Number of the Proposal	: No.DOR.9.1/Ph.D/PC/930/2021-22 dated 06.12.2022
Date on which the AEC meeting was held	: 08.02.2023
A clear statement of the decision reached AEC meeting (in the vent of the proposal is not approved, a statement of reasons for the same must be indicated	**: Approved**
Advice & suggestions (if any)	: The Participants information and participants/ caregivers consent form should be in the participant's/ caregiver's mother tongue.

Date: 10.02.2023

Signature & Name of the Member Secretary
Dr. Animesh Barman
Professor of Audiology
Department of Audiology
All India Institute of Speech and Hearing, Mysore-570006
Member Secretary
AIISH ETHICS
COMMITEE

Phone : 0821-2502000 / 2502100 Toll Free No. 18004255218 Fax : 0821-2510515,
e-mail : director@aiishmysore.in / @aiishmysuruofficial, @aiishmysuru.
website : www.aiishmysore.in

APPENDIX B

INFORMED CONSENT FORM

All India Institute of Speech and Hearing (AIISH), Manasagangothri, Mysore- 570006, Karnataka, India

Consent to Participate in a Research Study

Title of the study	**Cognitive Flexibility and Inhibitory Control in Adults with Hearing Loss**
Investigator	**Ms. Pooja C**
Guide	**Dr. Hema N**

I, Ms. Pooja C, Junior Research Fellow at All India Institute of Speech and Hearing (AIISH), Mysore, am conducting a study on cognitive flexibility and inhibitory control in adults with hearing loss. During the course of the study, I will be administering certain tasks which involve your active participation and cooperation. Audio recording of the sessions will be done for later analysis of responses. It is assured that these recordings will be kept confidential. There are no risks or discomforts involved during the study. Participation in the study is purely voluntary and not compulsory. You may choose to withdraw from the study at any point in time.

Informed Consent

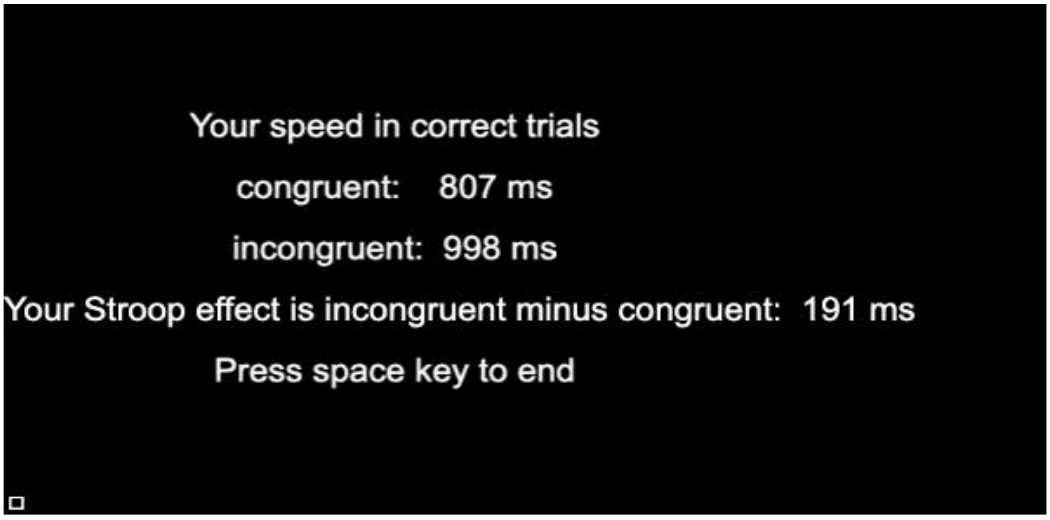
I have been informed about the study and understand its purpose and my participation in it. I understand that there are no risks involved in extending my participation as a human subject in the study. I understand that I have a right to refuse participation or withdraw my consent at any time. I willingly give my consent for my participation in this study.

Signature

(Name and Address)

APPENDIX C

SCREENSHOTS OF RAW DATA FROM THE STROOP TASK



Colum	Meaning
1	name of block
2	name of the word (e.g., "yellow")
3	the color the word is printed in (e.g., "red")
4	Stroop color match (1=compatible, 0=incompatible)
5	tablerow number
6	the pressed key number
7	Status (1=correct, 2=wrong, 3=timeout)
8	Response time (milliseconds)

training	yellow	green	0	2	2	1	1120
training	blue	red	0	16	1	1	1199
training	blue	blue	1	15	3	1	853
training	blue	yellow	0	13	3	2	288
training	green	blue	0	11	3	1	218
training	red	red	1	8	3	2	288
training	green	green	1	10	2	1	858
training	blue	red	0	16	1	1	1263
training	yellow	green	0	2	2	1	1167
training	green	green	1	10	2	1	761
training	blue	green	0	14	2	1	1001
training	blue	green	0	14	2	1	784
training	green	red	0	12	1	1	899
training	red	blue	0	7	3	1	1069
training	green	yellow	0	9	4	1	1101
training	green	green	1	10	2	1	909
training	red	blue	0	7	3	1	1038
training	red	green	0	6	2	1	1190
training	blue	blue	1	15	3	1	717
training	green	red	0	12	2	2	350
training	yellow	blue	0	3	3	1	829
training	red	blue	0	7	3	1	1250
training	red	yellow	0	5	4	1	923
training	yellow	green	0	2	2	1	814
training	green	yellow	0	9	4	1	1006
training	red	green	0	6	2	1	1021
training	blue	yellow	0	13	4	1	1212
training	green	blue	0	11	3	1	822
training	blue	red	0	16	1	1	1142
training	red	yellow	0	5	4	1	1181
training	yellow	blue	0	3	3	1	1053

APPENDIX D

SCREENSHOTS OF RAW DATA FROM THE GO/NOGO TASK

Colum	Meaning
1	Name of task: **go** or **nogo**
2	The response speed (in nogo trials, this is 2000, the timeout)
3	The error status (0 is correct, 1 is error)

go	480	0
go	224	0
nogo	260	1
go	326	0
go	317	0
nogo	2000	0
go	286	0
go	333	0
go	319	0
go	349	0
go	327	0
go	349	0
go	336	0
go	374	0
go	335	0
nogo	2000	0
go	269	0
nogo	294	1
go	332	0
nogo	2000	0
go	334	0
go	284	0

APPENDIX E

MEAN RANKS OF PERFORMANCE ON VERBAL FLUENCY TASKS BETWEEN AHL AND NTA

	Tasks	Groups	Mean Rank
Semantic Fluency	**Fruits**	**AHL**	13.89
		NTA	26.48
	Colors	**AHL**	12.42
		NTA	27.81
Phoneme Fluency	**Phoneme /n/**	**AHL**	15.37
		NTA	25.14
	Phoneme /p/	**AHL**	15.45
		NTA	25.07
Alternate Fluency	**Task 1**	**AHL**	17.32
		NTA	23.38
	Task 2	**AHL**	12.55
		NTA	27.69
	Task 3	**AHL**	12.53
		NTA	27.71

Note. AHL = Adults with hearing loss; NTA = Neurotypical adults

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ORIGINAL ARTICLE

Open Access

Executive functions in mid-life adults with mild sensorineural hearing loss compared with age-matched controls with normal hearing

Pooja Chandrashekar[1*] and Hema Nagaraj[1]

Abstract

Purpose This study explores the relationship between sensorineural hearing loss (SNHL) in mid-life adults and cognitive function, focusing on executive functions. Given the projected rise in dementia cases, identifying modifiable risk factors for cognitive decline is imperative. SNHL has emerged as a potential risk factor, with hearing loss accounting for a substantial portion of dementia cases. However, the cognitive implications of SNHL in mid-life adults are not well understood.

Method The study examined 50 participants, 25 with bilateral unaided mild SNHL (AHL) and 25 with normal hearing (ANH). A battery of audiological assessments and cognitive tests, including the Trail Making Test (TMT), was administered. TMT measures included direct scores (completion time and errors) and derived scores (difference, ratio, proportion, sum, and multiplication scores).

Results The AHL group displayed significantly poorer peripheral hearing compared to the ANH group, as reflected in pure-tone audiometry, speech reception thresholds, and speech identification scores. Significant differences were observed in all direct and derived TMT measures except for the ratio and proportion scores. This suggests that while overall cognitive disturbances were evident in the AHL group, they were not exclusive to executive function deficits. Notably, we did not identify any statistically significant effects of hypertension, diabetes, smoking, alcohol consumption, or physical activity on TMT scores.

Conclusion This study highlights the potential impact of SNHL on cognitive function in mid-life adults. Mid-life SNHL is associated with cognitive differences, emphasizing its role as a modifiable risk factor for future cognitive decline. This research underlines the need for further investigation into the cognitive effects of aided hearing and a multidisciplinary approach to understanding these alterations in cognitive function.

Keywords Sensorineural hearing loss, Cognitive function, Executive functions, Dementia risk, Mid-life adults

Background

It is commonly known that hearing loss is prevalent in older adults and sensorineural hearing loss (SNHL) is a widespread occurrence on a global scale [62]. The prevalence of hearing loss doubles with each successive decade of increased age and mostly begins during mid-life. For instance, approximately 27% of adults in their mid-life experience hearing loss [15]. However, there is a scarcity of research highlighting the increasing prevalence of hearing loss in mid-life. Such findings present potential opportunities for early intervention to mitigate the significant future impact of age-related hearing loss [84]. Hearing loss in mid-life not only acts as a potential risk factor for dementia [23] in older adults by influencing changes in brain structures but

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is also associated with increased late-life atrophy over time, particularly in specific temporal lobe structures involved in auditory processing and AD [6]. In recent studies, a strong link has been established between dementia and hearing loss, with the latter being identified as an independent but also a promising modifiable risk factor for incident dementia [3, 19, 20, 31–33, 37, 39, 56, 57, 69, 72, 81]. The causal mechanisms are discussed in detail elsewhere [86].

To date, there is limited data [63] that attempted to identify subtle cognitive changes that occur in early mid-life adults (between 45 and 55 years of age) with hearing loss as it has been observed that 55 years is the youngest mean age [32] at which the presence of hearing loss increased the risk of dementia. Previous studies have considered a wide array of neuropsychological tests to assess the cognitive abilities of their study participants including tests to examine the executive function (EF) [61]. There are three core components of EF, namely, cognitive flexibility, inhibitory control, and working memory [65]. The Trail Making Test (TMT) [71] is a test that employs these components for its execution. Part A of the TMT primarily evaluates attention, visual scanning, speed of eye-hand coordination, and information processing whereas Part B assesses working memory and EF, specifically the capacity to transition between sets of stimuli [54, 64, 73]. Previous studies have demonstrated that TMT can effectively predict changes in individuals with MCI [14, 26, 38] and AD [16]. The TMT has been sensitive to EF [73] impairments and has consistently produced significant findings across multiple clinical [8, 36, 51, 67] and aging population [60]. Moreover, its sensitivity also extends to various neurological processes [53, 64, 76]. Although completion times for TMT-A and B are regularly used in clinical practice, derived scores are also employed for interpretive purposes [54, 64, 78]. Another noteworthy measure of interest is the number of performance errors [4, 79]. The most commonly utilized derived scores include the difference score (B-A), the ratio score (B/A), and the proportion score (B-A/A). The rationale for employing these scores is twofold. Firstly, they serve to mitigate the influence of individual variability in Part B by utilizing each subject as their own control. Secondly, these scores help eliminate the contributions of motor speed and visual scanning speed by comparing Part B to Part A. Several authors have contended that these derived scores represent more refined measures of EF compared to the direct scores [5, 9, 18, 24, 41–43, 50, 73, 79]. While the derived scores are recognized for their sensitivity to frontal lobe damage [79], it is worth noting that they emphasize distinct characteristics. The difference score is found to be influenced by demographic characteristics when compared to the ratio score [24, 42, 50]. Conversely, the sum and multiplication scores offer indicators of overall cognitive performance rather than focusing solely on EF [43, 51]. The present study aimed to compare the performance of the TMT direct scores (i.e., completion time and performance errors for Part A and Part B) and derived scores (i.e., difference, ratio, proportion, sum, and multiplication scores) in mid-life adults with and without hearing loss. It was hypothesized a priori that adults with hearing loss would perform similarly to those without hearing loss on the TMT.

Methods

Study participants

The sample size for the present study was calculated using G*power analyses [27] utilizing the mean and standard deviation obtained from the pilot study at the significance level (α) of 0.05 and power of the test (1-β) at 0.80 [75]. The analysis prescribed a sample size ranging from 5 to 10. Due to the availability of participants, a total of 50 participants were recruited for the study consisting of 25 adults with bilateral unaided mild hearing loss (AHL) (13 female,mean age: 50.44 ± 2.84 years) and 25 adults with normal hearing (ANH) (13 female,mean age: 49 ± 3.29 years). A purposive sampling method was employed to collect samples for the present study. Demographic information for both groups is reported in Table 1.

All participants were right-handed, native Kannada speakers, with normal or corrected vision. None of them had a history of communication disorders, learning disabilities, neurological disorders, traumatic brain injury, or psychiatric disorders. Individuals with a history of substance abuse, use of psychoactive medications, known causes of hearing loss such as noise exposure, injuries, ototoxicity, unilateral or bilateral continuous tinnitus, those using hearing aids and experiencing significant vision issues such as untreated cataracts, macular

Table 1 Demographic characteristics of participants

	AHL group	ANH group
Total *N*	25	25
Age in years mean (SD)	50.44 (2.84)	49 (3.29)
Gender *N*	13F/12M	13F/12M
Hypertension *N*(%)	6 (24.0)	7 (28.0)
Diabetes *N*(%)	8 (32.0)	3 (12.0)
Smoking *N*(%)	2 (8.0)	2 (8.0)
Alcohol consumption *N*(%)	4 (16.0)	3 (12.0)
Physical activity *N*(%)	12 (48.0)	11 (44.0)

AHL Adults with bilateral unaided mild hearing loss, *ANH* Adults with normal hearing. *F* indicates female, *M* indicates male

degeneration, glaucoma, and retinopathy were excluded. All the participants had more than 12 years of formal education and underwent the Montreal Cognitive Assessment (MoCA), with a cut-off score of < 26 to eliminate potential cognitive impairment. Information regarding the presence or absence of hypertension, diabetes, smoking, alcohol consumption, and regular physical activity was also noted as these factors play an important role in accelerating cognitive decline.

Ethical considerations

The present study was approved by the Ethical Committee for bio-behavioral research involving human subjects at the All India Institute of Speech and Hearing (AIISH), Mysuru, India (Reference code: No.DOR.9.1/Ph.D/PC/930/2021-22). The participants were recruited for the study only after obtaining their written consent as per the ethical guidelines for bio-behavioral research involving human subjects of the All India Institute of Speech and Hearing [11]. All the participants and their caregivers were explained about the procedure and the approximate duration required for the tests. They were assured of safety during testing and confidentiality regarding their personal details.

Audiological evaluation

All participants underwent a comprehensive audiological assessment that included an otoscopic examination to eliminate the possibility of outer ear diseases, tympanometry to confirm the normal functioning of the middle ear, reflexometry to identify any abnormalities in the reflex pathways, along with both pure-tone and speech audiometry tests. Air conduction (AC) and bone conduction (BC) pure-tone thresholds were assessed in both ears using the modified Hughson-Westlake procedure [13]. Thresholds were recorded for octave frequencies ranging from 250 Hz to 8000 Hz for AC and 250 Hz to 4000 Hz for BC, respectively. The hearing thresholds for AC and BC were obtained using TDH-50P supra-aural headphones (Telephonics, Farmingdale, NY, USA) and a B71 bone vibrator (Radioear, KIMMETRICS, Smithsburg, MD, USA), respectively. The pure tone audiometry was carried out using Inventis Piano, a two-channel diagnostic audiometer (Inventis, 35127 Padova, Italy).

Speech recognition threshold (SRT) was obtained through live presentation of a standardized spondee word list in Kannada [70] which was within ± 12 dB HL of the pure-tone average threshold. Speech identification scores in quiet were determined using standard phonemically balanced word lists in the Kannada language [89] developed at the All India Institute of Speech and Hearing. All participants achieved speech identification scores exceeding 90% in quiet conditions. Tympanograms were obtained using a 226-Hz probe tone. Acoustic reflex thresholds were assessed for both ipsilateral and contralateral responses at frequencies of 500 Hz and 1000 Hz. It was confirmed that all participants exhibited normal middle ear function in both ears, as evidenced by 'A' type tympanograms and normal ipsilateral and contralateral acoustic reflex thresholds at 500 Hz and 1000 Hz. The immittance evaluations were performed using GSI-Tympstar Middle ear Analyzer (Grason Stadler Inc.-GSI-61,Milford, NH, USA). All tests were conducted in acoustically treated rooms.

The hearing sensitivity of the ANH group was within normal limits of ≤ 15 dB HL at frequencies 250 Hz to 8000 Hz for AC and 250 Hz to 4000 Hz for BC. The hearing sensitivity of the AHL group was between 25 dB HL to 40 dB HL [17] for similar frequencies for both AC and BC which was diagnosed as bilateral mild SNHL by a certified Audiologist.

Since the age difference equivalent to the cognitive decline linked with a 25-dB rise in hearing loss is 7 years, [55] adults with unaided mild SNHL were considered for the study. The study was carried out during the initial visit of the participants where they were diagnosed as having hearing loss for the first time. All the participants with reduced hearing sensitivity were directed towards hearing rehabilitation which mostly suggested the use of hearing aids.

EF tests

Trail making test

Part A Participants were instructed to connect 25 numbered circles sequentially by drawing lines connecting them as quickly and correctly as possible. Timing commenced as soon as participants were prompted to begin using a stopwatch. The examiner pressed the stopwatch as quickly and accurately as possible as soon as the participant started and finished the test. Whenever an error was made the examiner crossed out the erroneous line and provided immediate feedback. The test was discontinued if the participant failed to complete the test within 300 seconds.

Part B Participants were instructed to connect encircled numbers and letters, alternating between the two sequences (e.g., 1-A-2-B, and so on) consecutively in a progressive manner, up to the number 13. Commencing the timing, providing feedback for errors, and discontinuing the test were conducted following the same procedures as those employed in Part A. The entire TMT test including both Part A and B was administered in accordance with the protocol outlined by Bowie and Harvey [12]. Both tests were carried out using paper and pen in

a single session. Instructions were provided at the most comfortable level (MCL) through the audiometer and the participants were required to repeat the instructions before starting the test to ensure they understood the test instructions. If the participants were able to repeat the instructions appropriately, the examiner began the test. If they failed to, instructions were given to the participants again. The test was commenced only after the participants repeated the test instructions correctly. We adhered to this protocol with the concern towards participants with hearing loss as they took part in the study in an unaided condition, and our goal was to confirm that the reduction in hearing sensitivity did not impede their comprehension of the task instructions.

Scoring

The TMT yielded a total of four direct scores and five derived scores. The direct measures of performance encompassed the time taken to complete both Part A and B, as well as the number of errors made during these tests separately. From the direct scores, five derived scores were computed that included difference score (B-A), ratio score (B/A), proportion score (B-A)/A, sum score (A+B), and multiplication score (AxB/100). It is important to note that lower direct scores and higher derived scores indicate superior performance on the test.

Statistical analysis

Data analysis of this study was performed using the Statistical Package for Social Science (SPSS) version 20. Demographic data and the TMT scores are presented using descriptive statistics including the mean, standard deviation, sum of ranks, and mean ranks. Following data analysis for normality of distribution by the Shapiro–Wilk test, it was found that the TMT scores were not normally distributed. Since the scores were not normally distributed, alternative non-parametric tests have been employed in the present study. Mann-Whitney *U* test was carried out to find out the significance of the difference between AHL and ANH groups on the selected dependent variables that included both direct and derived TMT scores.

Results

Significant differences were observed between AHL and ANH groups for all the audiological measures as indicated by the Mann-Whitney *U* test in Table 2. The smaller U values obtained for the differences in values of audiological measures were all found to be significant at the .001 level. The mean ranks obtained for AHL and ANH groups were 38 and 13 respectively for right PTA ($p = .001$), the mean ranks obtained for left PTA for AHL and ANH groups were 38 and 13 respectively with a significance level of .001, and the mean ranks obtained for the right SRT were 37.98 and 13.02 respectively ($p = .001$), the mean ranks obtained for left SRT measure for AHL and ANH groups were 38 and 13 respectively with the significance level of .001. In all of the above-mentioned audiological measures, the AHL group had significantly higher values than the ANH group. However, in the case, the mean ranks obtained for right SIS percent were 16.10 and 34.90 with a significance level of .001 as well as in the case mean ranks obtained for left SIS percent were 13.72 and 37.28 with a significance level of .001, whereas the ANH group had higher values than AHL.

Mann-Whitney *U* test revealed significant differences between ANH and AHL groups (refer Table 3) in most of the TMT measures except for B/A ($p = .377$), and B-A/A ($p = .377$). In the case of TMT A, the mean ranks obtained for 13.96 and 37.04 with a significance level of .001, the mean ranks obtained for TMT A error were 22.32 and 28.68 respectively with a significance level of

Table 2 Results of audiological measures between AHL and ANH groups

Audiological measures	AHL group Mean (SD)	ANH group Mean (SD)	ANH group mean rank (sum of ranks)	AHL group mean rank (sum of ranks)	*p* value
Right PTA (dB HL)	10.40 (4.02)	33.26 (4.49)	38 (950)	13 (325)	.001*
Left PTA (dB HL)	10.55 (3.21)	33.20 (4.23)	38 (950)	13 (325)	.001*
Right SRT (dB HL)	5.66 (4.15)	30.60 (6.17)	37.98 (949.50)	13.02 (325.50)	.001*
Left SRT (dB HL)	4.62 (3.20)	33.20 (6.10)	38 (950)	13 (325)	.001*
Right SIS (%)	99.68 (1.10)	94.64 (3.77)	16.10 (402.50)	34.90 (872.50)	.001*
Left SIS (%)	99.84 (0.80)	93.44 (3.02)	13.72 (343)	37.28 (932)	.001*

AHL Adults with bilateral unaided mild hearing loss, *ANH* Adults with normal hearing. *PTA (dB HL)* = pure-tone average (decibels hearing level), *SRT (dB HL)* = speech reception threshold (decibels hearing level), *SIS* = Speech Identification Score

* $p < .001$

Table 3 Results of Mann-Whitney *U* test for TMT scores between AHL and ANH groups

TMT measures	ANH group Mean rank (sum of ranks)	AHL group Mean rank (sum of ranks)	*p* value
TMT A	13.96 (349)	37.04 (926)	.000*
TMT A error	22.32 (558)	28.68(717)	.038*
TMT B	14.60(365)	36.40(910)	.000*
TMT B error	21.10(527.50)	29.90(747.50)	.025*
B-A	19.16(479)	31.84(796)	.002*
B/A	27.32(683)	23.68(592)	.377
B-A/A	27.32(683)	23.68(592)	.377
A+B	13.52(338)	37.48(937)	.000*
AxB/100	13.32(333)	37.68(942)	.000*

AHL Adults with bilateral unaided mild hearing loss, *ANH* Adults with normal hearing, *TMT A* Trail-making test Part A, *TMT B* Trail-making test Part B

* $p < 0.05$

.038, the mean rank obtained for TMT B were 14.60 and 36.40 respectively with the significance level of .025, the mean ranks obtained for TMT B error were 21.10 and 29.60 respectively with the significance level of .025. The mean ranks obtained for ANH and AHL groups for B-A parameter were 19.16 and 31.84 with a significance level of .002. The mean ranks obtained for A+B parameters were 13.52 and 37.48 with a significance level of .001. Lastly, the mean ranks obtained for AxB/100 measure were 13.32 and 37.68 respectively with the significance level of .001. In all the above-mentioned measures AHL group had higher values than the ANH group. Box plots for direct and derived measures of TMT are depicted in Figs. 1 and 2 respectively.

Discussion

This study examined differences in performance on direct and derived measures of TMT between AHL and ANH groups. We found significant differences between the two groups on PTA, SRT, and SIS scores. The AHL group exhibited higher scores on PTA and SRT, and lower SIS scores relative to the ANH group, indicating poorer peripheral hearing. Findings revealed significant group differences in all the direct and derived measures of TMT except the ratio and proportion scores.

The findings of the present study are in agreement with the previous studies employing TMT B, where group differences were observed between older adults with hearing loss and normal hearing controls [1, 7, 40, 56, 57, 75].

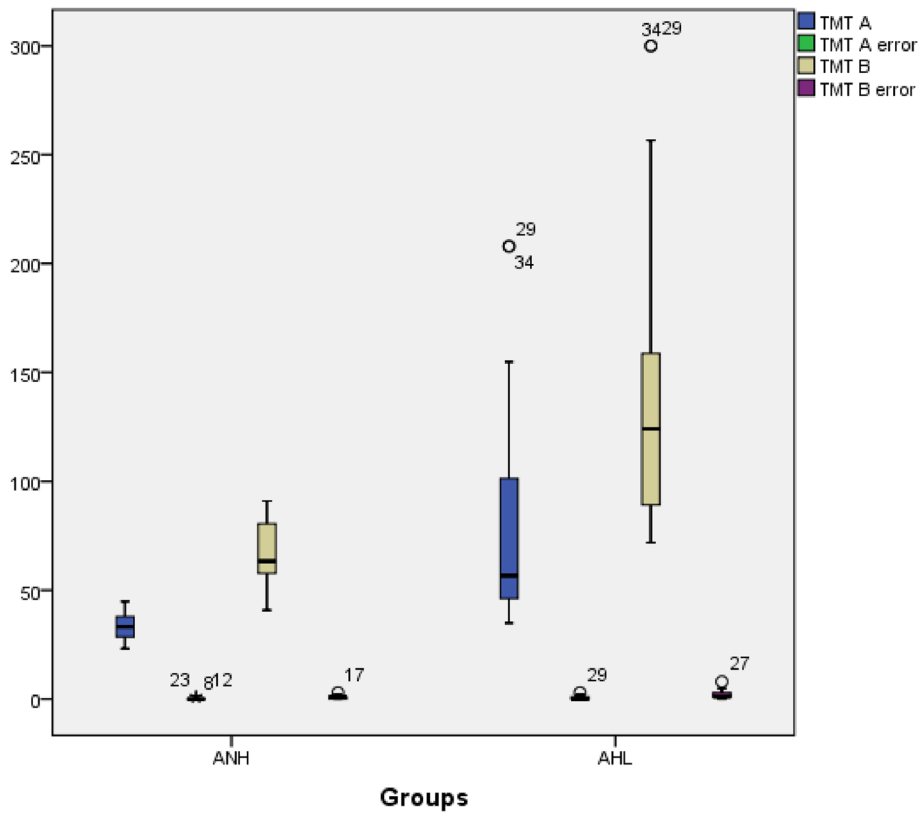

Fig. 1 Box plots for direct measures of TMT for ANH and AHL groups

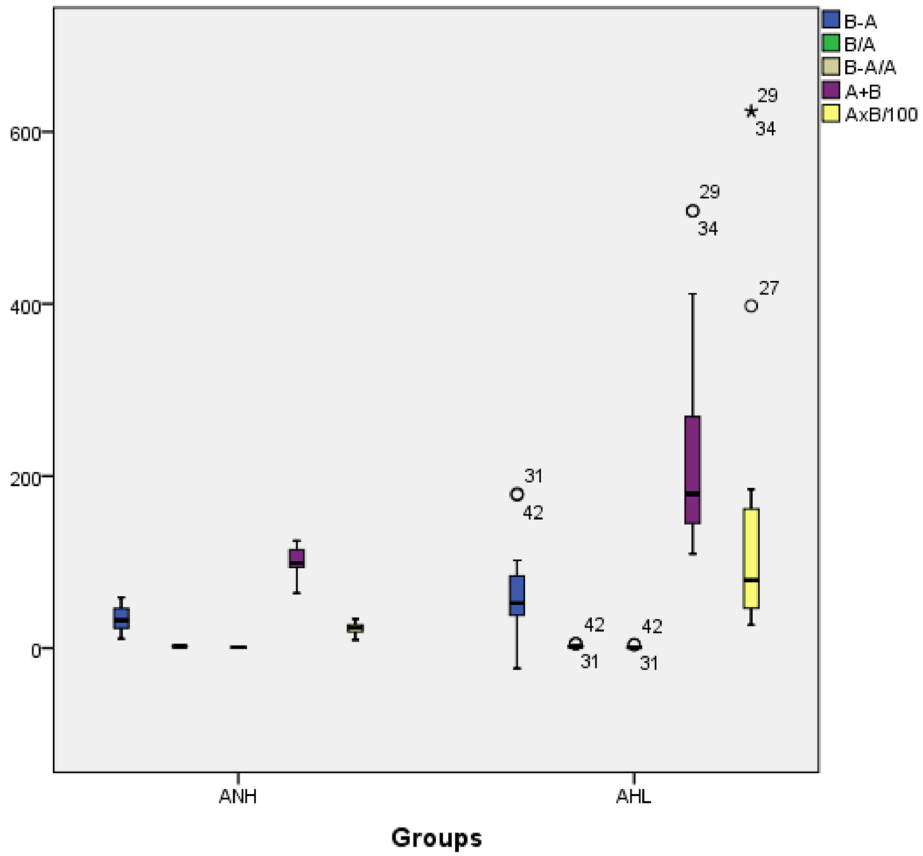

Fig. 2 Box plots for derived measures of TMT for ANH and AHL groups

The control group performed significantly better than the clinical group in the raw completion times, number of errors, and derived scores that resulted from difference, sum, and multiplication. However, we did not find any significant difference in the ratio and proportion scores. This variability introduces the challenge of interpreting TMT performance, especially in relation to the derived scores which could be attributed to the subject's demographic characteristics. The ratio and proportion scores are considered to be the most sensitive indices within the TMT for identifying deficits in EF. This is due to their lower susceptibility to the influence of demographic characteristics, as indicated by previous studies [18, 50]. While we did observe a notable distinction in TMT measures, we did not identify a variance in the most sensitive EF indices. This suggests the effect of demographic characteristics play an important role in disrupting the overall cognition that does not exclusively pertain to EF.

In this light, we observed the effect of hypertension, diabetes, smoking, alcohol consumption, and physical activity on TMT scores. However, our analysis did not yield any statistically significant findings. Since these conditions are previously known to be associated with increased dementia risk [59], the present results are contrary to the previous studies. One possible explanation for our results is that prior studies have primarily focused on considerably older populations compared to the participants in our study. Additionally, the long-standing effects of these conditions could potentially exert a detrimental influence on cognitive abilities over time [45].

The present study adds to the extensive research over decades that has indicated a link between sensory abilities, particularly hearing and cognitive performance [10, 44, 49, 58, 68, 80, 88]. This association suggests that cognitive decline due to hearing loss may commence during midlife, emphasizing its pivotal role as a significant modifiable risk factor for the subsequent development of dementia. While the acceptance of hearing loss as an independent and modifiable risk factor for dementia is widespread, its specific impact in midlife as a potential harbinger of cognitive consequences in later life remains inadequately elucidated [23]. An alternative perspective suggested that midlife hearing loss could potentially be an outcome of preclinical neurodegeneration rather than a causal factor [48, 85]. The present study supports this

notion by demonstrating significant differences in the TMT measures between the ANH and AHL groups.

One of the significant reasons for the results obtained in the present study could potentially be attributed to methodological disparities in the previous studies, particularly in the context of audiological assessments. For instance, certain studies relied on self-assessed hearing measurements from participants, and the criteria for hearing loss varied. In some studies, the range of normal hearing was considered up to 25 dB [55]. In our study, we meticulously adhered to a rigorous and standardized methodology. Notably, at the time of our investigation, the participants had not undergone any form of auditory rehabilitation, such as the use of hearing aids. In contrast, the participant groups in prior studies displayed heterogeneity, with some individuals employing hearing aids while others did not, considering that hearing loss is a reversible sensory deficit [66]. By diligently controlling for these variables, our study potentially unveiled significant differences across various TMT measures, shedding light on the impact of these methodological distinctions.

The observed variation in TMT performance could be due to alterations in auditory pathways resulting from peripheral hearing loss, which in turn may affect cognitive control [29]. Cohort studies suggest that even a mild degree of hearing loss may increase the risk of cognitive decline in individuals who initially exhibit cognitive intactness but are hearing-impaired at the baseline [21, 22, 30, 32, 39, 55–57, 83, 87]. The literature has put forth several potential hypotheses to elucidate this connection between hearing loss and cognitive changes including the cognitive load on perception hypothesis, the information degradation hypothesis, the sensory deprivation hypothesis, and the common cause hypothesis [82]. These mechanisms have the potential to deplete cognitive resources that are otherwise available for various cognitive functions. This, in turn, could contribute to the depletion of cognitive reserve and hasten the emergence of preclinical indicators of cognitive decline leading to dementia [2, 77].

On a similar line, a study among Chinese centenarians and oldest-old adults revealed that the occurrence of cognitive decline and depression was notably higher among individuals with HL compared to those without. Participants with HL exhibited significantly lower cognitive test scores, suggesting more pronounced cognitive decline, and experienced higher levels of depression [28]. Further, a systematic review of twenty-three studies found a substantial link between HL and mild cognitive impairment (MCI) [52]. The majority of studies reviewed indicated a notable association between peripheral HL and MCI. This finding is significant as EF is one of the areas commonly impacted in individuals with MCI which again supports the link between HL and subsequent cognitive decline. Research focusing on performance within distinct cognitive areas, such as processing speed, episodic memory, and EF, rather than overall cognitive assessments, has revealed moderate connections with hearing loss across these domains [40]. Numerous cohort studies and meta-analyses have highlighted a correlation between SNHL and cognitive impairment. Specifically, using pure tone audiometry, HL has been linked to lower scores across various neuropsychological tests evaluating multiple cognitive domains, including memory, language, and EF [74]. This association has been consistently observed across both small and large observational studies [25, 34, 46], as well as in cross-sectional and longitudinal population-based studies. Recent studies investigating the link between hearing loss and cognitive decline have utilized EF tests including TMT, indicating its effectiveness in this context [31]. A recent study demonstrated that steady assessments of fluid reasoning which is a part of EF and pure-tone auditory function showed considerable alteration over about seven years. During this timeframe, there was a decline in metabolic health and cognitive abilities, alongside an increase in hearing thresholds. These results suggest that significant age-related changes occur across various functional domains, even among middle-aged who are relatively healthy. Furthermore, the study found that lower cognitive performance correlated with elevated audiometric thresholds [35]. Another study that reviewed structural MRI studies revealed that HL is associated with accelerated atrophy of both total and regional brain volumes, along with reduced white matter integrity. Additionally, resting-state and task-based functional MRI studies indicated alterations in spontaneous neural activity and brain functional connectivity. It was concluded that these changes affect brain regions involved in auditory, language, cognitive, and affective processing independently of age [47]. From this perspective, it is clearly evident that HL impacts cognitive performance through a series of physiological changes that ultimately hinder brain function.

Limitations and future directions

To the best of our knowledge, this is the first study to investigate EF in midlife adults exclusively using TMT measures. While these tasks provide valuable insights, they may not fully capture the complexity of cognitive processes affected by SNHL. It is important to note that participation in our study was limited to individuals with untreated hearing loss. Further investigation is necessary to delve into the effects of aided hearing on EF, as well as to determine whether aided hearing can ameliorate these changes. The current study utilized a cross-sectional design, limiting the ability to establish causal

relationships between mild SNHL and EF deficits using the TMT. Conducting longitudinal studies to track cognitive changes over time can provide insights into the progression of EF deficits and how they relate to the severity and duration of SNHL. Such studies could also explore whether interventions such as hearing aids or cognitive training programs influence the trajectory of cognitive changes. Studies investigating cognitive function across various levels of hearing loss, ranging from mild to severe can better understand how auditory impairment impacts executive functioning. The study may have also had specific sample characteristics that limit the generalizability of findings to broader populations. A comprehensive understanding of the alterations found in the present study necessitates a multidisciplinary investigative approach encompassing behavioral, neuroimaging, and electrophysiological methodologies.

Conclusion

This study delves into the cognitive consequences of SNHL in mid-life adults, focusing on executive functions. While the research confirms that SNHL is linked to overall cognitive disturbances, the impact is not exclusive to executive function deficits, suggesting a broader cognitive influence. The results obtained in the present study accentuate the importance of early intervention for mid-life hearing loss, shedding light on a potential avenue for preventing cognitive decline and mitigating the future burden of dementia.

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Authors' contributions
PC conceived and designed the study, collected and analyzed the data, and drafted and edited the manuscript. HN assisted in the study design, provided critical revisions to the manuscript, and edited the manuscript. Both authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The present study was approved by the Ethical Committee for bio-behavioral research involving human subjects at the All India Institute of Speech and Hearing (AIISH), Mysuru, India (Reference code: No.DOR.9.1/Ph.D/PC/930/2021-22). The research study adhered to all ethical guidelines and regulations, ensuring informed consent, confidentiality, and protection of participants' rights throughout the research process.

Consent for publication
The participants were recruited for the study only after obtaining their written consent for publication as per the ethical guidelines for bio-behavioral research involving human subjects of the All India Institute of Speech and Hearing.

Competing interests
The authors declare that they have no competing interests.

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ORIGINAL ARTICLE

Verbal Fluency as a Measure of Executive Function in Middle-Aged Adults with Mild Sensorineural Hearing Loss

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Abstract
This study investigates verbal fluency as an indicator of executive function in middle-aged adults with mild sensorineural hearing loss, comparing them to age-matched controls with normal hearing. In this study, 50 middle-aged participants were recruited, comprising 25 with bilateral unaided mild hearing loss and 25 age-matched controls with normal hearing. Demographic information, including age, gender, and health-related factors, was collected. Audiological evaluations confirmed the participants' hearing status, and verbal fluency tests were conducted, encompassing semantic, phonemic, and alternate fluency tasks. Significant differences in audiological measures were observed between both groups. Verbal fluency tests revealed lower mean ranks between the groups on almost all tasks suggesting distinct accuracy and error patterns. This study establishes a link between mild sensorineural hearing loss and executive function in middle-aged adults, evidenced by deficits in verbal fluency tasks. The findings underscore the need for targeted interventions to address cognitive impairments, emphasizing the importance of comprehensive care strategies for individuals in this population.

Keywords Verbal Fluency · Executive Function · Middle-aged Adults · Sensorineural Hearing loss · Normal Hearing

Introduction

A relation between hearing loss (HL) and compromised executive function (EF) has been established by existing literature [1–6]. Several mechanisms have been proposed to elucidate the connection between HL and impaired EF which are supported by behavioural and neuroimaging research [7]. The diminished cognitive performance observed in individuals with HL appears to be rooted in a decrease in sensory input, resulting in reduced cognitive stimulation. For example, poorer hearing thresholds leading to poorer EF due to impaired speech perception [3], which in turn increasingly allocates EF to aid in speech perception to compromise for the loss of damaged regions in the auditory cortex due to HL [8]. EF refers to a set of cognitive processes that oversee and regulate one's thoughts and behaviours towards a specific overarching goal [9]. The core processes of EF are typically identified as cognitive flexibility, working memory, and inhibitory control [10, 11]. Cognitive flexibility encompasses the ability to update information, alter perspectives, and transition between tasks. The ability to perform a task involving cognitive flexibility relies on the support of both working memory and inhibitory control. Working memory plays a role in supporting short-term goals, information storage and processing simultaneously. Inhibitory control enables to restrain behaviour, reduce memory interruptions and mitigate irrelevant extraneous stimuli [10]. Since all three processes are interrelated, it is reasonable to assume that the tasks involving EF is invariably connected to these processes. One such task that is used widely are the verbal fluency (VF) tasks. These are commonly used in neuropsychological assessments, clinical practices, and research as a test of EF [12, 13].

The use of VF tasks can be attributed, at least in part, to the apparent face validity as assessments of EF. Participants are required to recall words from a given category within the specified time, a process that necessitates accessing their mental lexicon. Simultaneously, they must concentrate on the task, selecting words that adhere to specific constraints and avoiding repetition, thereby engaging in the EF processes [14]. For example, participants should keep the instructions in their mind and the prior responses they produced which

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is a reflection of the working memory [13, 15, 16], concurrently suppressing irrelevant responses and repetition [17]. Consequently, significant deficits in EF would likely result in subpar performance on VF tasks. Hence, these tasks serve as an efficient tool for evaluating EF.

While the semantic and phoneme fluency tasks are commonly used to assess VF, they share similarities as well as exhibit crucial differences in their task demands. Semantic fluency tests or word fluency tasks measure a person's ability to produce several words that fall under a specific category. Phoneme fluency tests or letter fluency tasks assess the ability to generate different words beginning with a particular sound. In each variant of the VF task, it is conceivable to adjust the demand on EF by incorporating a switching component known as the alternate fluency task. In this scenario, participants are asked to alternate between two distinct categories or phonemes within the same task, introducing an additional challenge to the EF processes. However, the relationship between HL and VF in older adults previously has yielded mixed results [6, 18, 19].

It is commonly known that hearing loss is prevalent in older adults and sensorineural hearing loss (SNHL) is a widespread occurrence on a global scale [20]. The prevalence of hearing loss doubles with each successive decade of increased age and mostly begins during mid-life. For instance, approximately 27% of adults in their mid-life experience hearing loss [21]. However, there is a scarcity of research highlighting the potential opportunities for early intervention to mitigate the significant future impact of age-related hearing loss [22].

To date, there is limited data [23] that attempted to identify EF changes that occur in early mid-life adults. Previous research has predominantly focused on the association between hearing loss and global cognitive decline, with limited attention directed towards specific EF [24]. Since EF changes appear early than other cognitive changes, VF is particularly relevant in this context, as it is imperative for a nuanced understanding of how mild SNHL, may influence specific cognitive domains. While studies have explored the cognitive consequences of severe hearing loss and the benefits of hearing interventions on cognitive outcomes [25, 26], there is a noticeable gap in the understanding of how mild SNHL, often underestimated in its impact, relates to specific aspects of EF. This study seeks to address this gap by employing VF tasks to scrutinize the potential cognitive ramifications of mild SNHL in middle-aged adults. Moreover, the current literature underscores the importance of considering age as a critical factor in the relationship between hearing loss and EF, with middle age being a pivotal period in cognitive aging trajectories [27, 28]. While VF deficits have been extensively documented in neurocognitive disorders [13], its exploration within the context of mild SNHL in middle-aged adults remains an underexplored area in the existing literature. Therefore, the present study aimed to compare the performance of the VF tasks that included semantic fluency, phoneme fluency and alternate fluency tasks in mid-life adults with and without hearing loss. Since the age difference equivalent to the cognitive decline linked with a 25 dB rise in hearing loss is 7 years, [3] adults with unaided mild SNHL were considered for the study. The study was carried out during the initial visit of the participants where they were diagnosed as having hearing loss for the first time. All the participants with reduced hearing sensitivity were directed towards hearing rehabilitation which mostly suggested the use of hearing aids. It was hypothesized apriori that adults with hearing loss would perform similarly to those without hearing loss on the VF tasks.

Table 1 Demographic characteristics of participants

	AHL group	ANH group
Total N	25	25
Age in years Mean (SD)	50.44 (2.84)	49 (3.29)
Gender N (F indicates female; M indicates male)	13 F/ 12 M	13 F/ 12 M
Hypertension N(%)	6 (24.0)	7 (28.0)
Diabetes N(%)	8 (32.0)	3 (12.0)
Smoking N(%)	2 (8.0)	2 (8.0)
Alcohol consumption N(%)	4 (16.0)	3 (12.0)
Physical activity N(%)	12 (48.0)	11 (44.0)

Note: AHL = Adults with bilateral unaided mild Hearing Loss; ANH = Adults with Normal Hearing

Methods

Study Participants

The sample size for the present study was calculated using G*power analyses [29] utilizing the mean and standard deviation obtained from the pilot study at the significance level (α) of 0.05 and power of the test (1-β) at 0.80. The analysis prescribed a sample size ranging from 5 to 10. Due to the availability of participants a total of 50 participants were recruited for the study consisting of 25 adults with bilateral unaided mild hearing loss (AHL) (13 female; mean age: 50.44 ± 2.84 years) and 25 adults with normal hearing (ANH) (13 female; mean age: 49 ± 3.29 years). A purposive sampling method was employed to collect samples for the present study. Demographic information for both groups is reported in Table 1.

All participants were right-handed, native Kannada speakers, with normal or corrected vision. None of them had a history of communication disorders, learning disabilities,

neurological disorders, traumatic brain injury, or psychiatric disorders. Individuals with a history of substance abuse and use of psychoactive medications were eliminated. Known causes of hearing loss such as noise exposure, injuries, ototoxicity, unilateral or bilateral continuous tinnitus and those using hearing aids were excluded. Individuals experiencing significant vision issues such as untreated cataracts, macular degeneration, glaucoma, and retinopathy were also excluded. All the participants had more than 12 years of formal education and underwent the Montreal Cognitive Assessment (MoCA), with a cut-off score of > 26 to eliminate potential cognitive impairment. Information regarding the presence or absence of hypertension, diabetes, smoking, alcohol consumption and regular physical activity was asked to the participants. This was noted as these factors play an important role in accelerating cognitive decline.

Ethical Considerations

The present study was approved by the Ethical Committee for bio-behavioural research involving human subjects at the All India Institute of Speech and Hearing (AIISH), Mysuru, India (Reference code: No.DOR.9.1/Ph.D/PC/930/2021-22). The participants were recruited for the study only after obtaining their written consent as per the ethical guidelines for bio-behavioural research involving human subjects of the All India Institute of Speech and Hearing [30]. All the participants and their caregivers were explained about the procedure and the approximate duration required for the tests. They were assured of safety during testing and confidentiality regarding their personal details.

Audiological Evaluation

All participants underwent a comprehensive audiological assessment that included an otoscopic examination to eliminate the possibility of outer ear diseases, tympanometry to confirm the normal functioning of the middle ear, reflexometry to identify any abnormalities in the reflex pathways, along with both pure-tone and speech audiometry tests. Air conduction (AC) and bone conduction (BC) pure-tone thresholds were assessed in both ears using the modified Hughson-Westlake procedure [31]. Thresholds were recorded for octave frequencies ranging from 250 Hz to 8000 Hz for AC and 250 Hz to 4000 Hz for BC, respectively. The hearing thresholds for AC and BC were obtained using TDH-50P supra-aural headphones (Telephonics, Farmingdale, NY, USA) and a B71 bone vibrator (Radioear, KIMMETRICS, Smithsburg, MD, USA), respectively. The pure tone audiometry was carried out using Inventis Piano, a two-channel diagnostic audiometer (Inventis, 35127 Padova, ITALY).

Speech identification scores in quiet were determined using standard phonemically balanced word lists in the Kannada language [32] developed at the All India Institute of Speech and Hearing. All participants achieved speech identification scores exceeding 90% in quiet conditions. Tympanograms were obtained using a 226 Hz probe tone. Acoustic reflex thresholds were assessed for both ipsilateral and contralateral responses at frequencies of 500 Hz and 1000 Hz. It was confirmed that all participants exhibited normal middle ear function in both ears, as evidenced by 'A' type tympanograms and normal ipsilateral and contralateral acoustic reflex thresholds at 500 Hz and 1000 Hz. The immittance evaluations were performed using GSI- Tympstar Middle ear Analyzer (Grason Stadler Inc.-GSI-61; Milford, NH, USA). All tests were conducted in acoustically-treated rooms. The hearing sensitivity of ANH was within ≤ 15 dB HL at frequencies 250 Hz to 8000 Hz for AC and 250 Hz to 4000 Hz for BC. The hearing sensitivity of AHL was between 25 dB HL to 40 dB HL [33] for similar frequencies for both AC and BC which was diagnosed by a certified Audiologist.

VF Tests

Participants were seated comfortably in a quiet room and instructions were clearly given along with examples. Each participant completed 7 verbal fluency tasks in total that comprised of semantic fluency, phoneme fluency and alternate fluency tasks that required producing as many different words as possible within 60 s. In the semantic fluency task, the participants were to produce words in two semantic categories: fruits and colours. In the phoneme fluency task, the participants were asked to produce words beginning from two phonemes in Kannada: /n/ and /p/. In the alternate fluency task, the participants were instructed to alternate the words in 3 conditions. (1) Alternate between two semantic categories: animals and vegetables, (2) alternate between two phonemes: /r/ and /s/, and (3) alternate between the semantic category of common objects and the phoneme /k/. The participants were instructed to perform the task without using proper nouns, reiterating previously named words or using the same word with a different prefix or suffix. Timing commenced as soon as participants were prompted to begin using a stopwatch. The examiner pressed the stopwatch as quickly and accurately as possible as soon as 60 s were completed and instructed the participants to stop the task. The participants were required to repeat the instructions before starting the test to ensure they understood the test instructions. If the participants were able to repeat the instructions appropriately, the examiner began the test. If they failed to do so, instructions were given to the participants again. The test commenced only after the participants repeated the test

instructions correctly. We adhered to this protocol with the concern towards participants with hearing loss as they took part in the study in an unaided condition, and the goal was to confirm that the reduction in hearing sensitivity did not impede their comprehension of the task instructions.

Scoring

A score of 1 was allocated for each accurate word response, while a score of 0 was assigned for every incorrect word response provided by the participants during the semantic and phonemic fluency tasks. With respect to the alternate fluency task, a score of 1 was provided for a correct alternate pair of words. A score of 0 was assigned when the participant either provided an incorrect response or failed to alternate between the specified pair. The number of errors was also noted in each task.

Statistical Analysis

The analysis of data in this study was conducted using Statistical Package for Social Science (SPSS) version 20. Demographic data and the VF scores are presented using descriptive statistics including sum of ranks and mean ranks. After conducting a data analysis to assess the normality of distribution using the Shapiro–Wilk test, it was determined that the VF scores did not follow a normal distribution. Consequently, in light of the non-normal distribution of scores, alternative non-parametric tests were utilized in this study. Mann-Whitney U test was carried out to find out the significance of the difference between AHL and ANH groups on the selected dependent variables that included accuracy and error scores.

Table 2 Results of audiological measures between AHL and ANH groups

Audiological measures	AHL group Mean (SD)	ANH group Mean (SD)	ANH Group Mean rank (sum of ranks)	AHL Group Mean rank (sum of ranks)	*p*-value
Right PTA (dB HL)	10.40 (4.02)	33.26 (4.49)	38 (950)	13 (325)	0.001*
Left PTA (dB HL)	10.55 (3.21)	33.20 (4.23)	38 (950)	13 (325)	0.001*
Right SRT (dB HL)	5.66 (4.15)	30.60 (6.17)	37.98 (949.50)	13.02 (325.50)	0.001*
Left SRT (dB HL)	4.62 (3.20)	33.20 (6.10)	38 (950)	13 (325)	0.001*
Right SIS (%)	99.68 (1.10)	94.64 (3.77)	16.10 (402.50)	34.90 (872.50)	0.001*
Left SIS (%)	99.84 (0.80)	93.44 (3.02)	13.72 (343)	37.28 (932)	0.001*

Note: AHL = Adults with bilateral unaided mild Hearing Loss; ANH = Adults with Normal Hearing. PTA (dB HL) = Pure-Tone Average (decibels hearing level); SRT (dB HL) = Speech Reception Threshold (decibels hearing level); SIS = Speech Identification Score.
* $p < 0.001$

Results

Significant differences were observed between AHL and ANH groups for all the audiological measures as indicated by the Mann-Whitney U test in Table 2. The smaller U values obtained for the differences in values of audiological measures were all found to be significant at 0.001 level. The mean ranks obtained for AHL and ANH groups were 38 and 13 respectively for right PTA ($p = 0.001$), the mean ranks obtained for left PTA for AHL and ANH groups were 38 and 13 respectively with the significance level of 0.001, the mean ranks obtained for the right SRT were 37.98 and 13.02 respectively ($p = 0.001$), the mean ranks obtained for left SRT measure for AHL and ANH groups were 38 and 13 respectively with the significance level of 0.001. In all of the above mentioned audiological measures AHL group had significantly higher values than ANH group. However, in the case of the mean ranks obtained for right SIS per cent were 16.10 and 34.90 with the significance level of 0.001 as well as in the case of mean ranks obtained for left SIS per cent were 13.72 and 37.28 with the significance level of 0.001, where ANH group had higher values than AHL.

Table 3 presents the results of the Mann-Whitney U test comparing VF scores between AHL and ANH groups.

In the semantic fluency task, significant differences were observed in accuracy for both categories, fruits ($p = 0.001$) and colors ($p = 0.001$), indicating lower mean ranks for the AHL group. However, no significant differences were found in the number of errors for fruits and colors ($p = 1.000$). In the phoneme fluency task, significant differences were observed for both accuracy and error scores for both the phonemes /n/ and /p/. In the alternate fluency task, significant differences were observed between the groups for accuracy in phoneme switching (alternating between phonemes /r/ and /s/) ($p = 0.001$) and for switching between category and phoneme (alternating between the category common objects and phoneme /k/) ($p = 0.001$) but not for category switching. With respect to errors, significant differences were observed for category switching (alternating between animals and vegetables) ($p = 0.002$) and for switching between category and phoneme (alternating between the category common objects and phoneme /k/) ($p = 0.030$).

Additionally we calculated the fluency difference score (FDS) as it has been proposed to more comprehensively encompass the influence of executive control in VF tasks (Friesen et al., 2015). The FDS is computed by taking the disparity in the number of correct responses between the semantic and phoneme fluency conditions and expressing it

Table 3 Results of Mann-Whitney U test for VF measures between AHL and ANH groups

VF measures	ANH Group Mean rank (sum of ranks)	AHL Group Mean rank (sum of ranks)	*p*-value
Semantic fluency			
Accuracy			
Fruits	33.42 (835.00)	17.58 (439.50)	0.001*
Colors	33.02 (825.50)	17.98 (449.50)	0.001*
Errors			
Fruits	25.50 (637.50)	25.50 (637.50)	1.000
Colors	25.50 (637.50)	25.50 (637.50)	1.000
Phoneme fluency			
Accuracy			
/n/	31.38 (784.50)	19.62 (490.50)	0.004*
/p/	31.04 (776.00)	19.96 (499.00)	0.007*
Errors			
/n/	21.28 (532.00)	29.72 (743.00)	0.011*
/p/	20.58 (514.50)	30.42 (760.50)	0.003*
Alternate fluency			
Accuracy			
Animals and vegetables	28.62 (715.50)	22.38 (559.50)	0.124
Phonemes /r/ and /s/	34.58 (864.50)	16.42 (410.50)	0.001*
Common objects and phoneme /k/	34.36 (859.00)	16.64 (416.00)	0.001*
Errors			
Animals and vegetables	20.94 (523.50)	30.06 (751.50)	0.002*
Phonemes /r/ and /s/	22.58 (564.50)	28.42 (710.50)	0.107
Common objects and phoneme /k/	21.80 (545.00)	29.20 (730.00)	0.030*
FDS 1	24.18 (604.50)	26.82 (670.50)	0.522
FDS 2	23.12 (578.00)	27.88 (697.00)	0.248

Note: Cells represent mean rank (sum of ranks). AHL = Adults with bilateral unaided mild Hearing Loss; ANH = Adults with Normal Hearing. VF = Verbal fluency. FDS = Fluency Difference Score * $p < 0.05$

as a ratio of correct responses in the semantic fluency condition. FDS 1 was calculated using the semantic category fruits and phoneme /n/, while FDS 2 was calculated using the semantic category colors and phoneme /p/. However, we did not delve deeper into FDS in the present study as no significant difference was observed between both the groups.

Discussion

This study examined differences in performance on different VF tasks between AHL and ANH groups. We found significant differences between the two groups on PTA, SRT and SIS scores. The AHL group exhibited higher scores on PTA and SRT, and lower SIS scores relative to the ANH group, indicating poorer peripheral hearing. These findings affirm the reliability of audiological assessments in delineating distinct hearing profiles of the study groups. Findings revealed significant group differences in accuracy of semantic fluency tasks, accuracy and errors in phoneme fluency tasks, accuracy of alternate fluency tasks between two phonemes and between a semantic category and a phoneme, errors in alternate fluency tasks between two semantic categories and between a semantic category and a phoneme.

This investigation revealed distinctions between AHL and ANH groups which potentially indicates the cognitive implications of mild SNHL in middle-aged adults. In the semantic fluency task, the AHL group exhibited significantly lower mean ranks for both fruits and colors categories. This aligns with studies suggesting that hearing loss may impact semantic memory and word retrieval processes [24]. Significantly, the retrieval of words involves either a phonological or a semantic search, imposing distinct requirements on phonological and semantic processing [34, 35]. With respect to semantic fluency, the present study found significant group differences that is contrasting compared to previous studies where no significant group differences were noted [6, 36, 37]. Most of the studies have reported differences in phoneme fluency tasks rather than semantic fluency tasks. Our results supported this finding that phonological representations and the capacity to manipulate these representations are negatively associated with hearing loss leading to poorer performance on phoneme fluency tasks [38, 39]. Significant group differences were also found for alternate fluency tasks in the present study which could be due to extra load on the cognitive flexibility to shift between the given categories and phonemes. The assessment of alternate fluency involves two primary aspects [40]. Firstly, intra-dimensional shifting necessitates individuals to alternate within the same domain. Secondly, extra-dimensional shifting involves generating words across different domains, such as alternating between a semantic category and a phoneme. Notably, distinct rule strategies may be employed for these aspects; intra-dimensional tasks involve alternating between rules of the same domain, while extra-dimensional shifting requires to switch between rules pertaining to different domains. Therefore, the former task entails switching within a single algorithm, while the latter requires two algorithms to shift between two distinct domains. This exerts an additional load on EF leading to poorer performance on alternate fluency tasks in AHL. However, the absence of significant differences in error rates implies that despite reduced verbal fluency, participants in the AHL group maintained accuracy in word production within the semantic categories. This was not true with phoneme fluency as the errors between both groups were significantly different underscoring the intricate relationship between mild SNHL and phonemic processing. This aligns with previous research suggesting that even mild hearing impairment may

impact the cognitive processes associated with phonological retrieval [13]. It also becomes necessary to explore the impact of certain demographic factors on VF. In this light, we observed the effect of hypertension, diabetes, smoking, alcohol consumption and physical activity on VF measures. However, our analysis did not yield any statistically significant findings. Since these conditions are previously known to be associated with increased dementia risk [41], the present results are contrary to the previous studies. One possible explanation for our results is that the prior studies have primarily focused on considerably older populations compared to the participants in our study. Additionally, the long-standing effects of these conditions could potentially exert a detrimental influence on cognitive abilities over time. This aligns with a study [42] that found an association between cardiovascular risk factors and cognitive decline may not be universally applicable across different populations. Similarly, studies exploring the effects of lifestyle factors such as smoking and alcohol consumption on cognitive function have reported mixed results, suggesting that the relationship may be influenced by various contextual factors [43, 44]. The non-significance of these demographic aspects in relation to VF further highlights the need for targeted research to elucidate the multifaceted factors influencing cognitive outcomes in individuals with mild SNHL.

The present study adds to the extensive research over decades that has indicated a link between sensory abilities, particularly hearing and cognitive performance [45–48]. This association suggests that cognitive decline due to hearing loss may commence during midlife, emphasizing its pivotal role as a significant modifiable risk factor for subsequent development of dementia. While the acceptance of hearing loss as an independent and modifiable risk factor for dementia is widespread, its specific impact in midlife as a potential harbinger of cognitive consequences in later life remains inadequately elucidated. An alternative perspective suggested that midlife hearing loss could potentially be an outcome of preclinical neurodegeneration rather than a causal factor. These findings are consistent with the intricate nature of verbal fluency, where different cognitive processes come into play. The observed discrepancies underscore the importance of considering task-specific variations in VF assessments when studying individuals with mild SNHL. Furthermore, the observed differences in VF patterns imply that AHL may face challenges in rapidly accessing and retrieving words based on specific conditions. This finding aligns with the notion that hearing plays a crucial role in phonological encoding and retrieval processes. Notably, this study delved into error rates, revealing significant differences which suggest potential difficulties in maintaining cognitive flexibility and inhibiting irrelevant responses among participants in the AHL group. These findings emphasize the need for a comprehensive examination of both correct responses and errors to capture the full spectrum of cognitive processes involved in VF tasks.

This study contributes to the limited literature exploring the cognitive consequences of mild SNHL, particularly in middle-aged adults. While existing research has predominantly focused on the elderly population and severe hearing loss [27, 28], these findings emphasize the need for targeted investigations into the cognitive effects of mild hearing impairment during middle age. This study advances the understanding of specific cognitive processes affected by mild hearing loss by applying a diverse set of VF tasks. However, the scarcity of literature directly addressing the relationship between mild SNHL and VF persists. Despite the established link between hearing loss and cognitive decline [3], studies exploring EF in mild SNHL remain underrepresented. This emphasizes on the novelty and significance of this study, contributing valuable data to a field with a pronounced research gap.

Limitations and Future Directions

The current study utilized a cross-sectional design, limiting the ability to establish causal relationships between mild SNHL and executive function deficits. The study may have had specific sample characteristics that limit the generalizability of findings to broader populations. Future studies should aim for more diverse and representative samples to enhance the external validity of results. The study relied on specific cognitive assessment tasks to evaluate executive function. While these tasks provide valuable insights, they may not fully capture the complexity of cognitive processes affected by SNHL. Future research could employ a broader range of cognitive measures to obtain a more comprehensive understanding of cognitive impairment in SNHL. Conducting longitudinal studies to track cognitive changes over time can provide insights into the progression of cognitive deficits and how they relate to the severity and duration of SNHL. Such studies could also explore whether interventions such as hearing aids or cognitive training programs influence the trajectory of cognitive decline. Studies investigating cognitive function across various levels of hearing loss, ranging from mild to severe can better understand how auditory impairment impacts cognitive functioning. Studying individuals across different age groups could provide insights into age-related differences on cognitive effects of SNHL. Comparing cognitive performance between middle-aged adults and older adults with SNHL could reveal age-specific patterns of cognitive decline and help tailor interventions accordingly.

Conclusion

This study provides evidence of the association between mild SNHL and EF, as assessed through VF tasks, in middle-aged adults. The observed differences in audiological measures and VF patterns highlight variations in the cognitive impact of mild SNHL in middle-aged adults. The AHL group exhibited significant deficits in most of the VF tasks, suggesting potential challenges in accessing, retrieving specific lexical information and phonological processing. Additionally, distinct differences in alternate fluency tasks further underscore the complexity of EF in the context of the AHL group. These findings contribute valuable insights into the cognitive implications of mild SNHL, emphasizing the need for targeted interventions to address potential EF deficits in middle-aged adults. Recognizing and addressing such cognitive aspects is crucial for developing comprehensive care strategies that enhance the audiological and cognitive well-being along with overall health of individuals affected in this age group.

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Author Contributions PC: Conceived and designed the study, collected and analysed the data, and drafted and edited the manuscript. HN: Assisted in the study design, provided critical revisions to the manuscript and edited the manuscript.

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Data Availability The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval and Consent to Participate The present study was approved by the Ethical Committee for bio-behavioural research involving human subjects at the All India Institute of Speech and Hearing (AIISH), Mysuru, India (Reference code: No.DOR.9.1/Ph.D/PC/930/2021-22). The research study adhered to all ethical guidelines and regulations, ensuring informed consent, confidentiality, and protection of participants' rights throughout the research process.

Consent for Publication The participants were recruited for the study only after obtaining their written consent for publication as per the ethical guidelines for bio-behavioural research involving human subjects of the All India Institute of Speech and Hearing.

Competing Interests The authors declare that they have no competing interests.

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