THE IMPACT OF COCHLEAR IMPLANTATION ON COGNITIVE FUNCTION IN ADULTS

by

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ABSTRACT

Background: The association between hearing loss and dementia have been found in past research. As both hearing loss and dementia are more prevalent in late adulthood, this results in a growing attention in age-related hearing loss. Despite the investigation done by numerous studies, a clear consensus of the causal relationship between the two has not been found yet, especially among those with severe-profound hearing loss.

Aims: The goal of this study was to explore the potential relationship between hearing loss and cognition in the older adult population. Aims were: to investigate the effect of hearing loss simulation on cognitive performance on normally-hearing individuals; to investigate whether presenting stimuli through different sensory modalities could affect cognitive performance on individuals with and without hearing loss and cochlear implants; and, to investigate the potential effect of severe-profound sensorineural hearing loss on cognitive performance with and without cochlear implants.

Methods: In the current study, hearing loss simulation groups were added. Data were collected from 26 participants (10 normally-hearing, 10 normally-hearing with simulated hearing loss at 70dB HL, 4 normally-hearing with simulated hearing loss at 60dB HL, 1 cochlear implant user, and 1 participant with hearing loss). To provide sufficient power for analysis, these findings were combined with data from earlier research (Phase 1) that adopted the same methods as were used for the present thesis (Phase 2) Digit Span and Arithmetic tasks from WAIS-IV were used to assess cognitive performance, presented in auditory and visual modalities. The scores from both modalities were then compared. Phase 1 data have been combined with Phase 2 data for data analysis using IBM SPSS statistical software.

This results in a data analysis of 58 participants in total, with data from 32 participants in Phase 1 (11 normally-hearing, 11 cochlear implant users, and 10 participants with hearing loss).

Results: There was an interaction between modality (visual or auditory) and cognitive test (digit span or arithmetic) across all groups. This manifested as Digit Span scores being slightly higher in the visual modality while the Arithmetic scores were much higher in visual modality. There was also a significant interaction between modality and hearing group. In the Digit Span test, all groups performed worse in the visual modality except the 70 dB hearing loss simulation group. For the Arithmetic test, all groups performed better in the visual modality.

Conclusions: The findings supported the cognitive load and overdiagnosis hypotheses that hearing loss provides a disadvantage in cognitive assessments due to limited cognitive capacity for working memory thus resulting in poor cognitive performance. This also highlights the protective effect of hearing assistive devices from cognitive decline.

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LITERATURE REVIEW

1.1 Introduction to hearing loss

The World Health Organization (WHO) released the first World Report on Hearing on 2 March 2021, where it is estimated that by 2050 almost one in every four people worldwide would have some degree of hearing loss, which would involve nearly 2.5 billion people worldwide (WHO, 2021). Among 2.5 billion, at least 700 million will require hearing rehabilitation, thus indicating this as a global health issue.

Hearing loss is defined as having a hearing threshold greater than 20 decibels hearing level (dB HL) in the better ear according to WHO (2021), where it is classified as 'disabling' hearing loss from the threshold of 35dB HL, and rehabilitation will be required. Hearing loss can occur in only one ear or both ears. Having said that, hearing loss can lead to a negative impact in life, including communication difficulties, education, speech and language development in children, cognition, mental health, employment, and relationships (Ciorba et al., 2012; Stevenson et al., 2010).

Among different types of hearing loss, age-related hearing loss (ARHL) is getting more attention among researchers, with hearing loss becoming one of the major concerns in the elderly population from the perspective of cognition (Vos et al., 2017). With the rise in life expectancy, a growth in the elderly population is estimated (Tran et al., 2021). As a result, the attention on the relationship between ARHL and cognitive decline has been growing as studies suggest that the elderly population will double by the year 2050. Therefore, a sharp increase in people with cognitive impairment and dementia will be expected (Prince et al., 2016).

1.1.1 How hearing works

In order to understand how hearing loss may occur, an understanding of the peripheral auditory system would be helpful. The peripheral auditory system involves the outer ear, middle ear, and inner ear, and all these three components work together to transmit sounds from the outer environment to the brain (i.e., auditory cortex) (Musiek & Baran, 2018). The outer ear involves the part of the ear which is visible to us. This consists of the pinna and the external auditory meatus (EAM) or known as the ear canal. Sound enters the EAM through the pinna which collects and directs the sound waves from the outer environment. As sound waves travel through EAM, they are directed to the middle ear. The middle ear consists of the tympanic membrane, middle ear space, Eustachian tube, and ossicular chain. The ossicular chain is composed of the three smallest bones in the human body – malleus, incus, and stapes.

The tympanic membrane, also known as the eardrum, functions as a divider between the outer ear and middle ear (Musiek & Baran, 2018). The middle ear cavity extends from the tympanic membrane to the inner ear and also the Eustachian tube. The Eustachian tube connects to the nasopharynx and equalizes the air pressure in the middle ear cavity. It also ensures the ventilation of the middle ear cavity to prevent middle ear infections. The ossicular chain functions as a "sound amplifier" where sound transferred from the outer ear through the tympanic membrane is amplified while transmitted to the inner ear (Musiek & Baran, 2018). The transmission of sound from the middle ear to the inner ear through the ossicular chain occurs by having the malleus, the first bone of ossicular chain, attached to the tympanic membrane, followed by the incus and stapes. The footplate of stapes is attached to the oval window of the cochlea, therefore transmitting sound signals into the cochlea.

The inner ear consists of the cochlea and vestibular system. The cochlea is the hearing part of the inner ear. It is a spiral-shaped cavity in the bony labyrinth, composed of three different fluid-filled compartments (Musiek & Baran, 2018). The compartments are known as scala vestibuli, scala tympani, and scala media. Both scala vestibuli and scala tympani contain perilymph, while scala media contains endolymph. The basilar membrane runs along the length of the cochlea, separating both scala media and scala tympani. It has different stiffness and mass across its length – giving variations in mechanical properties along the length and frequency tuning properties as it vibrates.

As the footplate of the stapes pulls and pushes into the oval window, this causes displacement of the fluid in the cochlea, creating a travelling wave along the basilar membrane. The Organ of Corti, a core component of the cochlea, lies on the basilar membrane in between the scala tympani and scala media. It comprises sensory hair cells known as inner hair cells (IHCs) and outer hair cells (OHCs), with nerve fibers connected to them. The displacement of fluid causes movement of the stereocilia on top of the hair cells, resulting in depolarization of the hair cells. The depolarization process then generates action potentials that activate the transmission of electric signals from the afferent auditory nerve fibers to the auditory cortex.

1.1.2 Hearing loss

Hearing loss is usually classified according to the type, degree, and configuration of loss. The degree of hearing loss is often categorized into normal, slight, mild, moderate, moderately severe, severe, and profound. This allows the clinician or any individuals to determine hearing thresholds ranging from 250Hz to 8000Hz, which are the frequencies tested in a standard pure tone audiometry (PTA).

PTA is a behavioural hearing test, meaning it requires responses from the individual being tested. The test is usually carried out by the audiologist presenting a tone from the audiometer through either inserts or headphones, and the individual would have to press a click-button when a tone is being heard. It is the most essential hearing test where the audiologist determines the softest levels that the individual is able to hear at different frequencies, through air conduction, also known as hearing thresholds (Schlauch & Nelson, 2015). Bone conduction thresholds are determined similar to air conduction testing, except a bone vibrator is used. A bone vibrator is usually placed on the mastoid behind the ear, where the outer ear and middle ear are bypassed, thus stimulating the cochlea directly. Air conduction occurs by the sound waves entering the ear canal reaching the eardrum, causing both the eardrum and ossicles to vibrate (Dalebout, 2008). The movement of stapes then results in a disturbance of fluids in the cochlea. On the other hand, bone conduction occurs by stimulating the cochlea directly when the bone vibrator causes the skull bones to vibrate. While the cochlea sits under the skull bones i.e., mastoid, this vibration causes disturbance of cochlear fluids therefore this effect triggers neural impulses from the hair cells in the cochlea.

Although healthy human ears are able to hear a wide range of frequencies ranging from 20 to 20000Hz, only those frequencies that are important for speech understanding are tested in PTA (Dalebout, 2008). Several hearing loss classification scales are used internationally. In New Zealand, the Goodman classification is being used. Hearing thresholds that fall at 15dB or lesser would be classified as normal hearing, meanwhile threshold from 90dB and above would be classified as profound loss. The table below shows hearing loss classification that is being used in New Zealand, at different hearing levels (dB HL) ranging from normal to profound (Table 1).

Hearing level (dB HL)	**Hearing loss label**
-10 to 15	Normal hearing
16 to 25	Slight hearing loss
26 to 40	Mild hearing loss
41 to 55	Moderate hearing loss
56 to 70	Moderate-severe hearing loss
71 to 90	Severe hearing loss
90 and above	Profound hearing loss

Table 1: Scale for classification of degree of hearing loss, adapted from Clark (1981), modified from Goodman (1965).

Hearing loss can also be described according to its configuration – this tells the clinician how much hearing loss there is at a specific frequency, across the audiogram (Dalebout, 2008). Besides, by looking at the shape of the hearing loss this could also help the clinician to determine the potential cause of the hearing loss. This is because some of the hearing disorders/impairments could be associated to a particular configuration. For example, individuals with Meniere's Disease tend to show a fluctuating low-frequency sensorineural loss on an audiogram, while individuals with noise-induced hearing loss tend to show a notch in the audiogram in the 4kHz region (Schlauch & Nelson, 2015).

The table below shows the classification of audiometric configuration that is being used in New Zealand (Table 2).

Term	Description
Flat	Less than 5dB average difference per octave
Gradually sloping	5-12dB increase per octave
Sharply sloping	15-20dB increase per octave
Precipitously sloping	Flat or gradually sloping, then threshold increasing at 25dB or more per octave
Rising	More than 5dB decrease per octave
Peaked, saucer	20dB or greater loss at the extreme frequencies, but not at the mid frequencies
Trough	20dB or greater loss at the mid frequencies, but not at the extreme frequencies
Notched	20dB or greater loss with complete or near-recovery at adjacent octave frequencies

Table 2: Criteria for classification of audiometric configurations (Carhart, 1945; Lloyd & Kaplan, 1978; Schlauch & Nelson, 2015).

The type of hearing loss is another method for clinicians to classify hearing loss where the physiology of the loss is determined – this allows clinicians to be able to determine the site of lesion along the auditory pathway. Different types of hearing loss will be discussed below.

1.1.2.1 Conductive hearing loss

As mentioned above, air conduction testing in PTA assesses the entire auditory pathway from the outer ear to inner ear. The outer ear and middle ear transmit sound waves to the cochlea therefore they are known as the conductive mechanism. A conductive hearing loss is known when there is a reduced efficiency of sound transmission through the outer and/or middle ear (Dalebout, 2008). This can be found from PTA where air conduction thresholds will fall out of the normal range with normal bone conduction thresholds. An air-bone gap can also be found where there is a difference between air conduction and bone conduction thresholds in the same ear.

A conductive hearing loss is commonly caused by cerumen in the ear canal, barotrauma, tympanic membrane perforation, otitis media, otosclerosis, or an infection in middle ear (Dalebout, 2008). A conductive loss could result in an attenuation of sound signals transmitting from outer ear to the cochlea, resulting in the individual perceiving sounds at a quieter level. Differing from sensorineural loss, a conductive loss does not result in distortions of sounds and can often resolve by use of drugs or surgery.

1.1.2.2 Sensorineural hearing loss

The sensorineural mechanism is made up of the cochlea and auditory nerve (Cranial Nerve VIII). When there is a damage or lesion in the sensorineural mechanism, a sensorineural hearing loss can be found (Dalebout, 2008). A sensorineural loss is determined through PTA when both air and bone conduction thresholds fall outside the normal range, with no air-bone gap detected. Air conduction thresholds show a hearing loss because the pathway includes transmitting sounds to the damaged cochlea followed by the auditory nerve. Bone conduction thresholds also show a hearing loss as it assesses the damaged cochlea or auditory nerve. This therefore explains the absence of an air-bone gap as both thresholds will be similar.

A sensorineural loss is possibly caused by noise exposure, ototoxic chemicals such as antibiotics, infection, autoimmune disorders, and genetic factors (Dalebout, 2008). The most common cause of sensorineural loss is ageing, also known as presbycusis or age-related hearing loss. Hearing loss can also occur at a higher level beyond the cochlea, such as at the nerve level or auditory cortex. This is known as retrocochlear hearing loss and is commonly caused by acoustic neuroma/vestibular schwannoma which is a growth of benign tumour on the auditory nerve (Dalebout, 2008).

1.1.2.3 Mixed hearing loss

When both air conduction and bone conduction thresholds fall outside the normal range (i.e., more than 15dB HL) with the presence of air-bone gap in the same ear, this indicates a conductive and sensorineural hearing loss exist in the same ear (Dalebout, 2008). This is known as mixed hearing loss where neither the conductive nor sensorineural mechanism is normal.

1.1.2.4 Impacts of sensorineural hearing loss

The effect of the damaged cochlea from a sensorineural hearing loss will be discussed further as this study investigates the relationship between sensorineural hearing loss and cognition. The damage on the cochlea due to sensorineural loss often arises from damage to the OHCs and IHCs (Moore, 2007). OHCs are usually more prone to damage than IHCs. Therefore, when OHCs are damaged this could cause several changes in hearing. The changes include reduced audibility, reduced frequency resolution, and loudness recruitment (Zeng & Djalilian, 2010).

Reduced audibility is caused by an elevation of absolute threshold. This elevation can occur through damage of OHCs and IHCs. When OHCs are damaged/lost, this results in impaired active mechanisms, causing reduced basilar membrane vibration at a low sound level (Moore, 2007). This leads to a more significant basilar membrane vibration required in order for OHCs to detect and transmit signal to the auditory cortex – meaning that a higher sound level would be required for a more significant basilar membrane vibration to occur. Furthermore, loss or damage of IHCs could result in impaired transmission of sound signals to the auditory cortex, therefore resulting in reduced audibility. In some cases, IHCs might be entirely damaged at a particular region on the basilar membrane, meaning no electric signals could be detected by the auditory nerve fibers in that region. It is also known as the 'dead region' (Moore & Glasberg, 1997). With loss of sensitivity of soft sound levels this could impact on the individual's speech intelligibility especially when differentiating weaker sounds such as the plosives /p/, /b/, /d/, /t/, and /k/ (Moore, 2007). This could therefore lead to misunderstandings in words or conversations.

Besides the loss of sensitivity, sensorineural loss also leads to reduced frequency resolution. Frequency resolution refers to the ability to separate the spectral components in a complex sound. The sounds we hear in our environment are made up of different frequencies and composed into a complex sound. For example, speech is a complex sound that consists of different frequencies ranging from 125Hz to 8kHz. The ability to resolve frequency depends on the OHCs on the basilar membrane (Moore, 2007). Frequency selectivity can be measured as psychophysical tuning curves. Loss of frequency selectivity is evidenced by broadened auditory filters (Zeng & Djalilian, 2010). This determines the ability of the individual to differentiate different speech sounds such as /k/ and /g/. Therefore, when OHCs are damaged, this leads to poor frequency selectivity (Oxenham & Bacon, 2003).

Sensorineural hearing loss can also lead to a change in loudness perception. Loudness is a subjective perception of an individual towards a sound – it can be scaled from 'inaudible', 'very soft', 'soft', 'medium/comfortable', 'loud', 'very loud', and 'too loud' (Epstein & Marozeau, 2010; Oxenham & Bacon, 2003). On average, individuals with normal hearing are able to hear sounds from 0dB SPL and tolerate sounds up to around 120dB SPL. This is known as the dynamic range (Epstein & Marozeau, 2010). Loudness is associated with basilar membrane velocity. During sound transduction, the travelling wave moves the basilar membrane in an up-down motion at the frequency of the sound. As the sound level increases, the amplitude of the up-down motion also increases. Therefore, the basilar membrane moves faster (higher velocity) as amplitude increases for a given frequency (Epstein & Marozeau, 2010).

On the other hand, when there is cochlear damage (i.e. sensorineural hearing loss), this leads to elevated absolute threshold, where the rate of growth of loudness level is more significant than normal. In normal hearing individuals, the growth of loudness is the power function of sound intensity over at least a dynamic range of 100dB; however, in hearing loss individuals, loudness grows in a more linear system leading to reduced dynamic range (Epstein & Marozeau, 2010). This phenomenon is known as loudness recruitment. It is a change in loudness perception due to damage to OHCs.

1.1.3 Hearing loss simulation

Many studies have been looking into methods to simulate hearing loss as well as cochlear implant processing. Researchers have been using different simulations in normal hearing individuals in order to isolate specific factors that might be related to sensorineural hearing loss. However, this is difficult to achieve due to the lack of homogeneity in individuals with sensorineural hearing loss, while the sensorineural loss may present differently to each individual. Therefore, the hearing loss simulation may not truly reflect a sensorineural loss, however this still provides insight for researchers into different aspects of hearing loss. This has also been used as a functional research tool in contributing into the improved development of hearing loss models. Besides, having a deeper insight into different hearing loss aspects leads to better treatments of hearing loss, such as improved hearing aids signal processing.

1.1.3.1 Filtering

Several approaches have been used in simulating different aspects of sensorineural hearing loss. One of the techniques involves frequency specific attenuation to investigate the reduced audibility caused by elevated thresholds observed in cochlear hearing loss. This technique is also known as filtering. Filtering is done by passing the stimuli through a pass or notch filter, and low-pass filtering has been widely used to simulate a cochlear hearing loss where the audibility of high frequency sounds is usually reduced.

Studies carried out filtering by attenuating signal at specific frequencies through a software (Bilger & Wang, 1976; Humes, Dirks, Bell, & Kincaid, 1986; Munro, 1995; Nazzi, Bertoncini, & Mehler, 1998; Wang, Reed, & Bilger, 1978). The signal is attenuated by a certain amount desired, resulting in a reduction in long term average sensation level of speech. This therefore allows researchers to simulate a perception of reduced audibility in individual with hearing loss. In Bilger and Wang (1976) and Wang et al. (1978), it was proposed that this method of simulation can provide an insight into consonant recognition in individuals with hearing loss, which is usually the most important aspect in speech recognition. For instance, Bilger and Wang (1976) found that those with a similar configuration of sensorineural loss tend to show similar errors in phonemic recognition. Similar results were also found in Wang et al. (1978), where similar consonant confusions were noticed in those with similar configurations of audiogram.

Low-pass filtering was used in Munro (1995) and Nazzi et al. (1998) with cut-off frequencies of 300 to 600Hz. It was mentioned that in this way, the details of consonants and vowels in the speech would be removed, therefore requiring individuals to depend on prosodic cues. Xu and Mok (2012) also carried out simulation in Mandarin and Cantonese speakers using low-pass filtering with cut-off frequencies of 150 to 300Hz. As both Mandarin and Cantonese are tonal languages, i.e. languages with different tone patterns to express different meanings or to distinguish between words, it was found that the intonation identification accuracy remained good meanwhile speech intelligibility decreased. From these studies, it could therefore suggest that using filtering could highlight the feature of reduced speech intelligibility however might not necessarily be the prosodic meaning in speech.

Kumar and Yathiraj (2009) simulated three different configurations of hearing loss (gradually sloping, sharply sloping, falling), aiming to investigate the perception of filtered speech in Indian-English speakers. The simulation was done through Adobe Audition software, with attenuation at specific frequencies for different hearing losses. Results showed that perception of filtered speech appeared to differ between different hearing loss configurations. This could be due to the fact that the acoustic characteristics of speech sounds lie in different frequency regions, thus perception of speech sounds would depend on cues available at different frequency regions in different configurations of hearing loss. It was therefore suggested that this simulation method would be effective in providing insight into the perception of speech sounds at a certain frequency with reduced audibility.

1.1.3.2 Spectral smearing

Several studies have used another simulation technique to investigate reduced frequency selectivity in cochlear hearing loss – spectral smearing. This method was designed by manipulating the spectrum of a speech signal. This allows a simulation of the broadening auditory filters, where in normal hearing participants with normal auditory filters would evoke an excitation pattern resembling those with broadened auditory filters (Baer & Moore, 1993). Furthermore, this simulation method allows researchers to isolate this aspect of cochlear hearing loss (i.e reduced frequency selectivity) from other effects such as time coding. Speech intelligibility is then measured in the simulated participants.

In Baer and Moore's studies, they looked into the effects of spectral smearing on speech intelligibility in noise. It was found that speech intelligibility remained high with spectral smearing in quiet speech, however had a significant impact on speech in noise with speech-to-noise ratio (SNR) of 0 and -3dB (Baer & Moore, 1993). In Baer and Moore (1994), the results were consistent with their previous study.

Nittrouer et al. (2015) simulated the broadened auditory filters on speech recognition in noise in adult and child participants. Child participants were involved as it is known that hearing loss could result in a more significant impact in language outcomes or academic achievement in children, therefore leading to a lower quality of life. Results showed diminished sentence recognition for participants across all ages, which is also consistent with Baer and Moore (1993, 1994) and ter Keurs et al. (1992, 1993).

1.1.3.3 Additive masking

One of the other techniques is additive masking noise. This technique allows researchers to investigate the reduced audibility caused by an elevated threshold, and reduced loudness perception which caused reduced dynamic range (Duchnowski & Zurek, 1995; Moore & Glasberg, 1993; Zurek & Delhorne, 1987). There are different approaches to achieving this simulation method. The first approach is known as equivalent threshold masking (ETM). ETM can be carried out by introducing masking noise that has been spectrally shaped into normal-hearing participants. This results in an elevation of detection thresholds to the level representative of those with cochlear hearing loss.

Zurek and Delhorne (1987) carried out a study to determine consonant recognition in noise in those with mild to moderate SNHL and also normal hearing participants with ETM simulation. Results showed no consistent difference between both groups, suggesting that loss of audibility could have a greater effect on reduced speech intelligibility rather than suprathreshold auditory deficits. They also reported that ETM is suitable to simulate the effects of SNHL at a mild to moderate level. However, with the level of masking noise required to introduce in normal hearing participants, this simulation approach is limited to losses up to around 70dB HL. This indicates that this method is not generally recommended to simulate severe SNHL and above as the noise level required becomes excessive.

The second additive masking approach is known as multiband dynamic expression (MDE). This method has been used in many studies such as Duchnowski and Zurek (1995), Lum and Braida (2000), Moore and Galsberg (1993), and Villchur (1973, 1974). MDE simulates loudness recruitment in cochlear hearing loss by applying level-dependent attenuation to input signals into normal hearing listeners, where the signals map the detection thresholds of the individual with hearing loss. The level-dependent attenuation allows researchers to simulate elevated thresholds and recruitment as the attenuation is applied in different frequency bands to map the tone levels. Normal hearing listeners with MDE simulation would be able to experience the abnormal growth of loudness with similar intensity as those with cochlear hearing loss. This therefore overcomes the limitation of ETM, where ETM could only simulate mild to moderate SNHL, MDE is able to simulate a more severe SNHL by attenuating sound towards the detection thresholds of the hearing loss individuals rather than introducing noise to elevate detection thresholds.

Villchur (1974) was one of the first researchers looking into these two approaches, ETM and MDE. Villchur compared the effect of both simulation methods on the perception of spoken sentences. It was reported that this simulation could suggest that loudness recruitment is a sufficient cause for reduced speech intelligibility.

Results also found that both simulation approaches tend to have very similar quality and intelligibility.

Furthermore, Duchnowski and Zurek (1995) suggested that MDE could also be used to simulate the effects of mild to moderate SNHL on speech intelligibility. They carried out a study investigating MDE on consonant recognition by using the same presentation conditions used in Zurek and Delhorne (1987). Moore and Glasberg (1993) applied filters to separate speech signals into a number of frequency bands, followed by applying an expansive non-linearity to each band. They also simulated high frequency loss by including more envelope expansion on the high frequencies. Though it was mentioned that MDE is suitable to simulate severe SNHL without putting uncomfortably loud masking noise for simulation, the use of level-dependent attenuation could result in stimuli presented at a lower SPL to those with hearing loss simulation compared to those with an actual hearing loss (Desloge et al., 2012).

Desloge and colleagues investigated the effects of audibility and age on masking in participants with hearing loss and hearing loss simulation (Desloge et al., 2010, 2011a, 2011b, 2012). The speech stimuli were presented in sentences with either interrupted or continuous noise. Desloge and colleagues combined both simulation approaches, i.e. ETM + MDE through the combination of spectrally shaped threshold noise and multiband expansion for octave bands with centre frequencies from 250Hz to 8kHz (Desloge et al., 2012). With this combination it was intended to mimic the effects of elevated thresholds as well as reduced dynamic range and loudness recruitment of SNHL.

In the previous studies carried out by Desloge and colleagues, it was reported that they were able to reproduce the speech intelligibility of those with hearing loss with ETM + MDE simulation (Desloge et al., 2010). Moreover, this combination was also able to simulate the effect of reduced frequency selectivity and loudness recruitment in SNHL (Desloge et al., 2011a, 2011b).

1.1.3.4 Combination techniques

Another technique that researchers have used to simulate cochlear hearing loss is by simulating several characteristics of cochlear loss by combining various stimuli. For example, Ariöz and Günel (2016) simulated the effects of reduced frequency selectivity with spectral smearing but also loudness recruitment and threshold elevation. The method used for spectral smearing was adapted from Baer and Moore (1993). For loudness recruitment and threshold elevation, the input signal was filtered to 13 center frequencies, and an auditory filter was applied to mimic a moderate to severe SNHL. Time alignment was applied to the outputs of the filter, and the input signal was decomposed into an envelope. The channels were then all combined to achieve an output sound.

To evaluate the reliability of the hearing loss simulation method, Ariöz and Günel (2016) used a modified rhyme test to assess speech intelligibility as a subjective measure and speech intelligibility index as an objective measure. The findings showed more reliable results in modified rhyme test in both noisy and no-noise environment, while speech intelligibility index showed similar results in the no-noise environment only. It was suggested this could be due to the speech intelligibility index being more sensitive to noisy environment. In conclusion, it was suggested that this simulation method is reliable and useable in general.

A recent study carried out by Füllgrabe (2020) investigated the impact of ARHL on the performance in a cognitive test. Test scores were compared between normal hearing group and simulated hearing loss group. The hearing loss simulation method adapted was from Nejime and Moore (1997), where they aimed to simulate several perceptual aspects of ARHL. These aspects include elevated hearing thresholds, reduced frequency selectivity by Baer and Moore (1994), and loudness recruitment by Moore and Glasberg (1993). The findings found that the simulation group showed a decline in cognitive performance, suggesting that the hearing loss simulation method used to be interpreted as a simulation of suprathreshold auditory processing deficits associated with ARHL. However, Füllgrabe (2020) suggested that the simulation used only mimicked perceptual aspects of ARHL to a moderate level, and no consensus has been achieved to present in simulating temporal processing abilities. It was also mentioned that because of this, the present study could have underestimated the actual impact of ARHL on cognitive performance.

In order to summarise different hearing loss simulation methods, a table below shows a summary of different studies of hearing loss simulation methods mentioned previously (Table 3).

Simulation method/Studies	Technique used	Summary of Findings
Filtering (Bilger & Wang, 1976; Humes, Dirks, Bell & Kincaid, 1986; Kumar & Yathiraj, 2009; Munro, 1995; Nazzi, Bertoncini, & Mehler, 1998; Wang, Reed, & Bilger, 1978; Xu & Mok, 2012)	Attenuation of signal at specific frequencies through a software	• Simulate perception of **reduced audibility** • Provide an insight on consonant recognition • However might not necessarily provide insight into the prosodic meaning in speech (Xu & Mok, 2012)
Spectral smearing (Baer & Moore, 1993; Baer & Moore, 1994; Nittrouer et al., 2015; ter Keurs et al., 1992; ter Keurs et al., 1993)	Manipulation of speech signal spectrum	• Simulate perception of **reduced frequency selectivity** • Manipulation of speech signal spectrum allows a resemblance of excitation patterns evoked in a cochlea with broadened auditory filters • Able to isolate this aspect from other effects such as time coding
Additive masking (Desloge et al., 2012; Duchnowski & Zurek, 1995; Lum & Braida, 2000; Moore & Glasberg, 1993; Villchur 1973; Villchur, 1974; Zurek & Delhorne, 1987)	Two approaches: Equivalent threshold masking (ETM): Introduction of spectrally-shaped masking noise	ETM: • Simulate perception of **reduced audibility and reduced dynamic range** • Suitable to simulate mild to moderate SNHL, limited up to 70dB HL • Not suitable for severe SNHL in general as the levels of noise required to elevate thresholds become excessive

	Multiband dynamic expression (MDE): Application of level-dependent attenuation in different frequency bands to map tone levels	MDE: • Simulate perception of **elevated threshold and reduced dynamic range** • Normally-hearing with MDE simulation would experience abnormal growth of loudness with similar intensity as those with SNHL • This overcomes the limitation of ETM, where MDE is able to simulate a more severe SNHL by attenuating sound toward the detection thresholds of SNHL individual, rather than introducing noise to elevate thresholds • However the use of level-dependent attenuation could result in stimuli presented at a lower SPL (Desloge et al., 2012) • Combination of ETM + MDE would allow the simulation of elevated thresholds, reduced dynamic range, and reduced frequency selectivity in SNHL
Combination techniques (Ariöz & Günel, 2016)	Combination of spectral smearing adapted from Baer and Moore (1993), simulation of loudness recruitment and threshold elevation using a loudness recruitment simulation algorithm	• Simulate the **combined suprathreshold effects of SNHL – reduced frequency selectivity, loudness recruitment and threshold elevation** • By using both objective and subjective measures (speech intelligibility index and modified rhyme

		test), findings showed that this simulation method is reliable and useable
(Füllgrabe, 2020)	Application of algorithm developed by Nejime and Moore (1997) to process the audio signals	• Simulate the **perceptual consequences of ARHL – elevated thresholds, reduced frequency selectivity, and loudness recruitment** • The simulation method used in this study only mimicked some aspects of ARHL at a moderate level • There is no consensus on simulating temporal processing abilities to present • The present study could be underestimating the actual effect of ARHL on cognitive performance

Table 3: A summary of studies of different hearing loss simulation methods used

1.2 Cognition

1.2.1 What is cognition?

Cognition in humans is the mental action or process of understanding, as well as recognizing and perceiving knowledge (Maturana, 1978). Cognition involves different mental processes such as problem-solving, reasoning, attention, memory, perception, learning, and language (Sachdev et al., 2014). In the latest edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5), six key domains of cognitive function are defined, where each of them has subdomains (Edition, 2013). The six key domains are perceptual-motor function, language, learning and memory, social cognition, complex attention, and executive function. Figure 1 shows the six different neurocognitive domains in DSM-5, with subdomains under each of them.

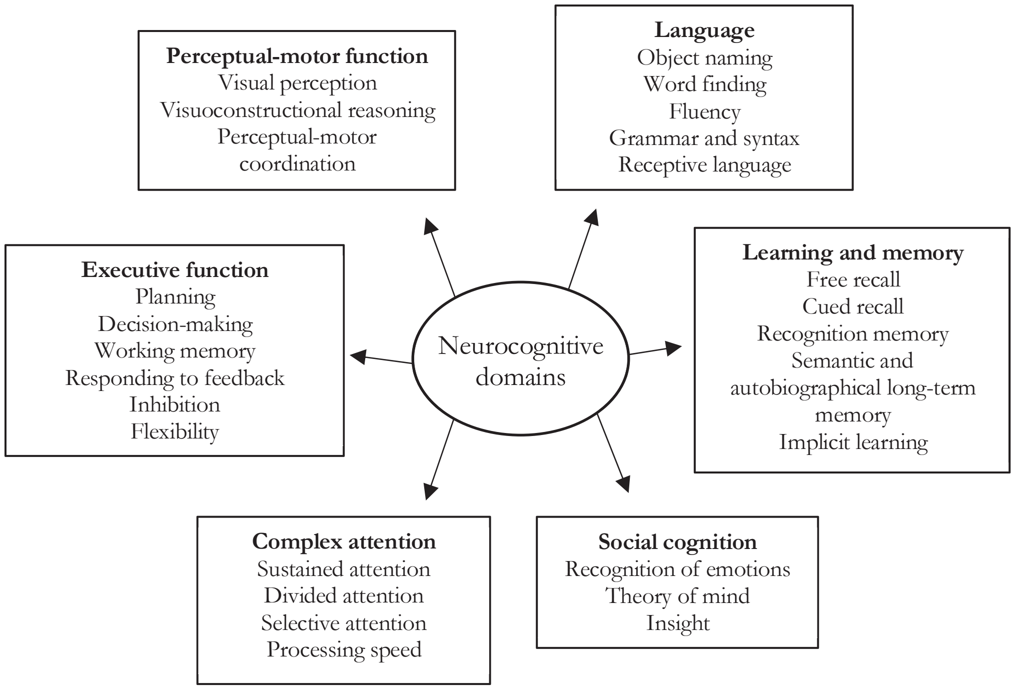

Figure 1: Six different neurocognitive domains that are defined by the Diagnostic and Statistical Manual of Mental Disorders (DSM-5), with subdomains underneath each domain (Edition, 2013).

According to DSM-5, perceptual-motor function allows an individual to perceive information through senses such as visual or touch to recognize and manipulate objects. This allows an individual to be able to interact with the environment. Language development involves both receptive and expressive. Receptive language involves the ability to understand; and expressive language refers to the ability to communicate ideas and thoughts through spoken or written words. Language includes its own structure such as semantics, syntax, phonology, morphology, and pragmatics. Learning and memory are important cognitive processes for people to encode, store, and retrieve new information. This information can also be synthesized and integrated with previous knowledge. Attention plays an important role with memory in learning, as it is a cognitive process that allows an individual to focus on a specific information that follows with creating memories. Attention helps an individual to determine which environmental stimuli to attend to – this hence aids in the ability to survive and allows people to avoid distractions to complete a specific task. Social cognition plays an essential role in determining how individuals process, store, and apply information in social contexts (Fiske & Taylor, 2013). This allows people to explain and predict their own behaviours and others (Bulgarelli & Molina, 2016). Lastly, the executive function refers to the high-level cognitive processing and is an essential part for every cognitive process. This involves decision-making, planning, responding to external environment, and working memory.

1.2.2 Executive function

Executive function can be known as the heart of most cognitive processes, where this involves high-level processing in order to carry out new behaviours and also facilitate everyday life circumstances (Gilbert & Burgess, 2018). This includes inhibiting, prioritizing, and maintaining behaviours, switching between tasks, integrating information to support the decision-making process, and categorizing and handling novel information or situations (Banich, 2009). The frontal lobe, primarily the prefrontal cortex, is responsible for executing these cognitive processes (Best & Miller, 2010; Olson & Luciana, 2008; Shimamura, 2000).

As the list of functions that fall in the executive function is comprehensive, it is therefore difficult to have a "gold standard" test to measure executive function. Instead, many different tests are used to assess different aspects of executive function. One of the tests often being used is the Wisconsin Card Sorting Test – this test measures the ability of an individual to display flexibility in the changing of reinforcement, to conclude and reason, and to display abstract thinking (Banich, 2009; Coulacoglou & Saklofske, 2017). Another test, the Stroop task, measures the ability of an individual to make decisions based on task information while facing distracting information (Banich, 2009). For example, the individual would be required to name the colour of the word presented while ignoring the word itself. This required the individual to use executive function to override word reading and focus on the colour of the word only (e.g., the word 'Red' presented with blue ink). This involves inhibition – overcoming the tendency of executing strong stimulus-response association.

The Tower of London task is one of the approaches used in assessing an individual's mental planning and problem-solving skills. This task involves the individual planning mentally a sequence of moves to reach a goal (Banich, 2009; Phillips et al., 2001).

The executive processes can be categorized into either automatic processing or controlled processing (Banich, 2009). Automatic processing is also known as routine processing, meaning the mental operations are well-learned and involuntary such as reading out a word or an experienced biker riding a bike. Not much attention is required in this process. On the other hand, controlled processing is known as non-routine processing, meaning the mental operations do not involve well-structured stimulus-response association. This processing invovles attention and effort, such as an individual learning to ride a bike for the first time.

Because the executive function is so crucial in carrying out self-directed behaviour, it is one of the abilities that could be affected by ageing (Treitz, Heyder, & Daum, 2007). Treitz and colleagues carried out a study investigating the effect of age on a range of executive processes. The findings showed an accelerated decline in cognition after the age of 60, including task management that requires the ability to manage divided attention tasks or coordination tasks (Treitz, Heyder, & Daum, 2007).

1.2.3 Working memory

Working memory is a cognitive mechanism that has a limited capacity to hold information, like a 'temporary sticky note' in the brain, in order to execute a task successfully. Working memory is known to have a close relationship with attention (Engle, 2002). Past researchers have suggested several models introducing the concept of working memory such as Atkinson's and Shiffrin's (1968) multi-store model and levels of processing model by Craik and Lockhart (1972).

The multi-store model by Atkinson and Shiffrin's (1968) proposed that there are three memory stores – a sensory register, short-term memory, and long-term memory. Each store has its own characteristics in terms of encoding, capacity, and duration (Atkinson & Shiffrin, 1968). It is assumed that the information input is being transferred in a linear way, similar to information processing of a computer with "input – process – output". As the information is being detected at short-term or long-term memory, it is processed by maintenance rehearsal in short-term memory and elaborative rehearsal in long-term memory. This multi-store model introduced a good understanding of short-term memory; however, it is too simplified where Atkinson and Shiffrin (1968) suggested that both short-term and long-term memory are performed in a unitary state.

As opposed to the multi-store model by Atkinson and Shiffrin (1968), the levels of processing model by Craik and Lockhart (1972) is non-structured and focuses on the depth of information processing in memory. No short-term or long-term memory were proposed in this model. In this model it is proposed that information can be processed in three different ways. Shallow processing involves structural processing and phonemic processing, where maintenance rehearsal takes place, while deep processing involves semantic processing, where elaboration rehearsal takes place (Craik & Lockhart, 1972). It is assumed that the deeper the processing level is, the easier the information can be retrieved as this is affected by how the information is encoded. Having said that, this model was criticized for its vague concept of 'depth' of processing which could not be objectively measured, and the relationship between 'deeper' processing and better memories was not explained (Eysenck, 1978).

Of all the models proposed, the most commonly used and widely cited in the literature is the multicomponent working memory model proposed by Baddeley and Hitch (1974) (Chai, Abd Hamid, & Abdullah, 2018). Baddeley's model consists of four major components. The main part is the central executive, or sometimes known as the executive control. The three subcomponents are known as visuospatial sketchpad, phonological loop, and episodic buffer.

In Baddeley's model, it is proposed that the central executive is the heart of working memory, important for executive function in cognitive processing (Baddeley & Hitch, 1974). It functions as a "control center" by directing or suppressing attention to information. It is responsible for information manipulation, recall, and processing, thus allowing the execution of meaningful tasks such as decision making and problem solving. The central executive has its own pool of attentional resources; however, it can deplete when overloaded.

The central executive is assisted by two auxiliary systems, the phonological loop and visuospatial sketchpad. They both have their own responsibilities at lower-level processing. The visuospatial sketchpad stores visual and spatial information temporarily for processes such as localization, navigation, and mental map information, while the phonological loop stores verbal information in a rehearsal-like buffer until the information is needed again. For example, if a person needs to generate and hold an image for further processing, visuospatial sketchpad in working memory is being used. On the other hand, if a person needs to recall information immediately or articulate information, the phonological loop is at work.

Another component, episodic buffer, was later introduced into the revised model (Baddeley, 2000). The episodic buffer was proposed to act as a temporary storage system that allows information to be transferred from long-term storage to working memory. It is also involved in the modulation and integration of sensory information – this means different types of information are combined, forming a complete memory. The figure below shows the working memory model proposed by Baddeley and Hitch (1974) and its four major components (Figure 2).

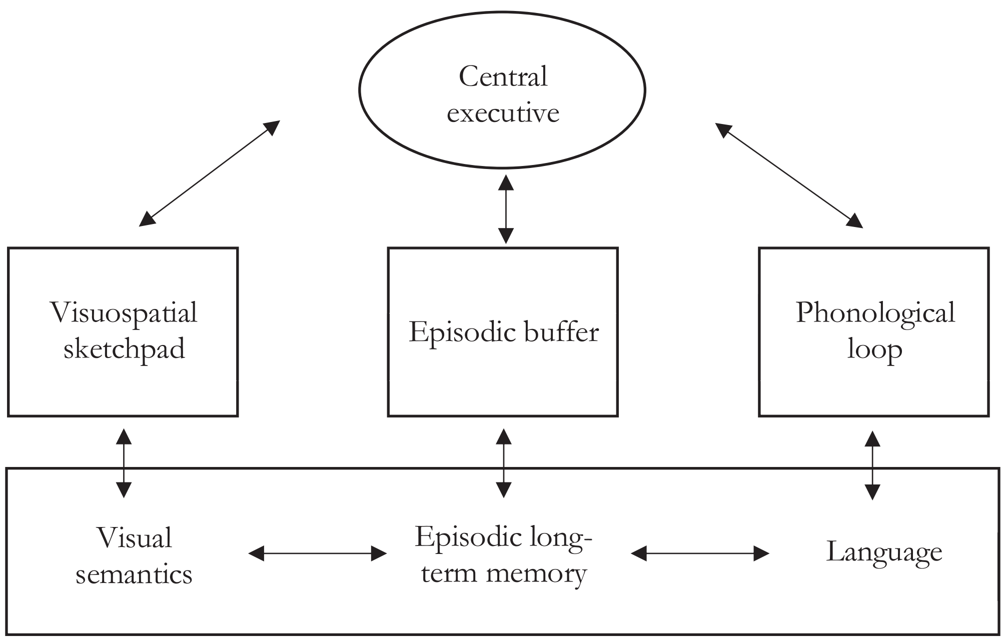

Figure 2: Working memory model by Baddeley and Hitch (1974), with its four components. Episodic buffer component added from Baddeley (2000).

1.2.4 The relationship between cognition and hearing loss

Research has shown clear evidence of the increasing prevalence of sensorineural hearing loss due to aging, also known as age-related hearing loss. Furthermore, with the increasing prevalence of cognitive decline in the older adult population, the association between sensorineural hearing loss and cognitive decline has been researched. Many studies have found the relationship between hearing loss and cognitive decline in older adults, including longitudinal studies and systematic review articles (Baltes & Lindenberger, 1997; Barnes & Yaffe, 2011; Dawes et al., 2015; Lindenberger & Baltes, 1994; Lin et al., 2004; Lin, 2011a; Peters, Potter, & Scholer, 1988; Tran et al., 2021), however the relationship remain unclear between these two factors. In this section, various hypotheses explaining the relationship between hearing loss and cognition will be introduced and discussed in order to understand the potential mechanisms linking the two aspects. This would then follow with a discussion of studies investigating the relationship between hearing loss and cognitive decline in the older adult population, as well as the findings from Phase 1 of this study.

1.2.4.1 Hypotheses linking hearing loss and cognitive decline

According to the report produced by The Lancet Commission on Dementia, Prevention, Intervention, and Care in 2020, it was reported that hearing loss was the most significant specific potentially modifiable risk factor for dementia (Livingston et al., 2020). Although dementia has been posing a global health challenge in many societies, the underlying mechanisms of the connection between the two are still not being well understood despite the various hypotheses linking the two proposed.

Uchida and colleagues introduced four different theories to explain how hearing loss and cognitive decline could be linked (Uchida et al., 2019). These theories include the cognitive load hypothesis, common cause hypothesis, cascade hypothesis, and overdiagnosis/harbinger hypothesis.

1.2.4.1.1 Cognitive load hypothesis

Cognitive load theory was developed by a psychologist John Sweller in 1998 (Sweller, 1994). It is proposed that the ability of an individual to perform a task depends on the cognitive load – the cognitive effort in information processing. Therefore, if a task requires too much cognitive capacity, performance will be hindered due to limited cognitive capacity in working memory. Avoiding cognitive overload is therefore recommended to optimize the use of working memory capacity. In the case of an individual with hearing loss, more auditory processing is needed due to degraded auditory information hence greater listening effort is needed. Listening effort refers to the attention required to understand auditory information like speech and environmental sounds. Listening effort would tend to be very low for normal-hearing individuals, however for individuals with hearing loss listening effort will increase significantly as the degree of hearing loss increase and when the listening environment becomes increasingly difficult. This leads to more auditory processing thus greater cognitive resources is needed, resulting in cognitive overload (Lin & Albert, 2014; Wayne & Johnsrude, 2015).

Effortful listening could potentially lead to brain structural changes and neurodegeneration from excessive cognitive load in individuals with hearing loss. This is because with hearing loss, more cognitive processing is needed thus distracts away from other cognitive process like working memory, therefore potentially leading to cognitive decline in the long run. Having said that, more research is still needed to show clear evidence of cognitive load hypothesis in hearing loss. Figure 3 below shows a visual representation of cognitive load hypothesis.

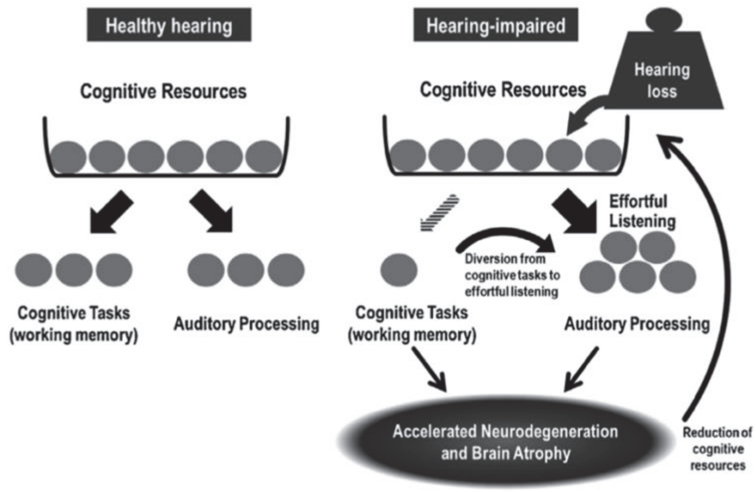

Figure 3: Cognitive load hypothesis. From "Age-related hearing loss and cognitive decline – The potential mechanisms linking the two", by Uchida et al., 2019, *Auris Nasus Larynx, 46*(1), 1-9. Copyright granted 2019 by Elsevier B.V.

1.2.4.1.2 Common cause hypothesis

The second hypothesis, common cause hypothesis, proposes that hearing loss and cognitive decline occur due to a common factor, that is due to the aging brain. It is proposed that hearing loss and cognitive decline occurs independently as a result of the common neurodegenerative process (Lin & Albert, 2014; Wayne & Johnsrude, 2015). For example, it has been found that age-related hearing loss can lead to physiological changes such as loss of hair cells and/or neurons, structural changes in stria vascularis, and even changes in central auditory pathways could occur. On the other hand, dementia is multifactorial, which could cause by several risk factors such as genetics, general physical health, oxidative stress, stroke, brain injury and more (Snowdon et al., 1997; Livingston et al., 2020). Figure 4 shows a visual representation of common cause hypothesis.

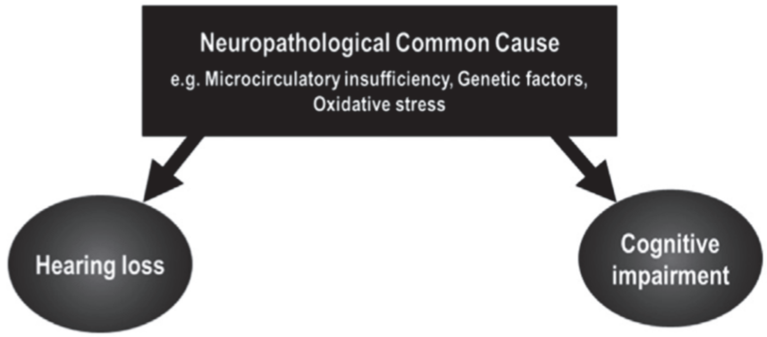

Figure 4: Common cause hypothesis. From "Age-related hearing loss and cognitive decline – The potential mechanisms linking the two", by Uchida et al., 2019, *Auris Nasus Larynx, 46*(1), 1-9. Copyright granted 2019 by Elsevier B.V.

1.2.4.1.3 Cascade hypothesis

The cascade hypothesis has a similar idea to the "use it or lose it" theory. The "use it or lose it" theory suggested that if an individual does not constantly use or practise an ability or skill, the individual might risk losing it due to the plasticity of brain. This also applies to the cascade hypothesis in auditory signal processing which proposes that prolonged hearing loss could lead to structural changes in the brain, especially auditory cortex due to lack of auditory stimulation. Researchers have found neurological changes in animal brains from the damaged cochlea (Xie et al., 2016; Park et al., 2018). In human studies, it was found that individuals with hearing loss tend to have smaller brain volumes and an increased rate of brain atrophy (Lin et al., 2014; Golub et al., 2017; Rigters et al., 2017).

Furthermore, hearing loss often causes communication breakdowns and limitations due to misinterpretation of information and reduced auditory input. This can interfere with the individual's participation in social environments and lead to social isolation. Studies have found evidence of poorer cognitive performance from perceived social isolation, and also increased rate of cognitive decline and depression (Sugawara et al., 2011; Mick, Kawachi, & Lin, 2014; Dawes et al., 2015). Therefore, social limitation caused by hearing loss could indirectly lead to depression, and this could then result in cognitive decline, either directly or indirectly (Cacioppo & Hawkley, 2009). Figure 5 shows a visual representation of the cascade hypothesis.

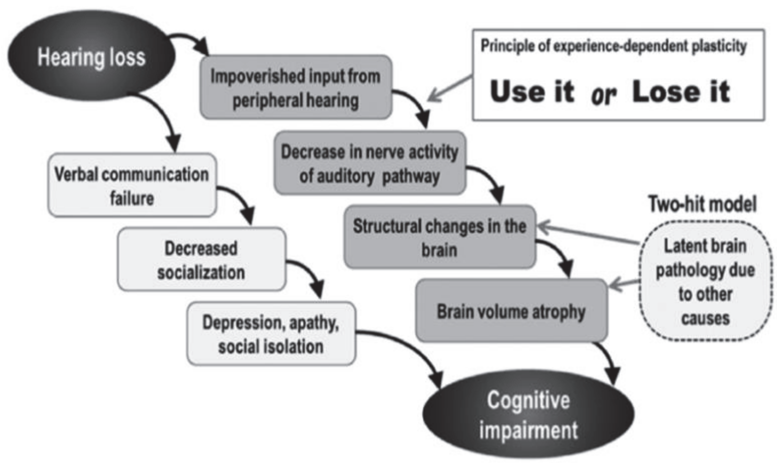

Figure 5: Cascade hypothesis. From "Age-related hearing loss and cognitive decline – The potential mechanisms linking the two", by Uchida et al., 2019, *Auris Nasus Larynx, 46*(1), 1-9. Copyright granted 2019 by Elsevier B.V.

1.2.4.1.4 Overdiagnosis/harbinger hypothesis

The fourth hypothesis proposes that the association between cognitive decline and age-related hearing loss is overdiagnosed. It is suggested that many cognitive tests use verbal instructions and thus rely on hearing – for individuals with hearing loss, are therefore at a disadvantage (Dupuis et al., 2015). With cognitive tests that rely heavily on verbal skills and verbal memory, it is considered not appropriate for those with hearing loss even if the response is executed nonverbally.

Jorgensen et al. (2016) carried out a study where they simulated hearing loss in young individuals with no cognitive issues. They completed tasks in Mini Mental

State Examination (MMSE) and the results showed that their scores were significantly affected by hearing loss and were misdiagnosed for dementia. It was therefore suggested that people with hearing loss could be misdiagnosed for or have the risk of overdiagnosis of cognitive impairment even though they might be cognitively sound.

Wong et al. (2019) completed a neuropsychological battery, Hopkins Verbal Learning Testing – Revised (HVLT-R), that includes auditory and visual versions, with normally-hearing participants and those with hearing loss. Both participant groups were age matched. Several testing conditions were carried out in their study – natural auditory condition (stimuli presented at normal speaking volume) and crossed auditory condition (stimuli presented at amplified volume to those with hearing loss and to normally-hearing participants under hearing loss simulation). Results showed that those with hearing loss but cognitively intact appeared to perform impaired in the cognitive test in auditory version, as well as those with simulated hearing loss. Both participant groups performed similarly in the visual version of HVLT-R. Wong and colleagues therefore suggested that tests that involve auditory stimuli may have lower validity, as overlooking the effect of hearing loss in individuals could potentially result in overdiagnosis of cognitive impairment among older adults.

Moreover, research has also found that older individuals with central auditory processing disorder (CAPD) may be misdiagnosed with dementia (Gates et al., 1996, Gates et al., 2008, Gates et al., 2011, Swords et al., 2018). This is because people with CAPD share similar symptoms as dementia such as poor attention and having difficulty understanding speech with background noise. This may result in these people being diagnosed with cognitive impairment while they are only experiencing hearing difficulty. Figure 6 shows a visual representation of overdiagnosis/harbinger hypothesis.

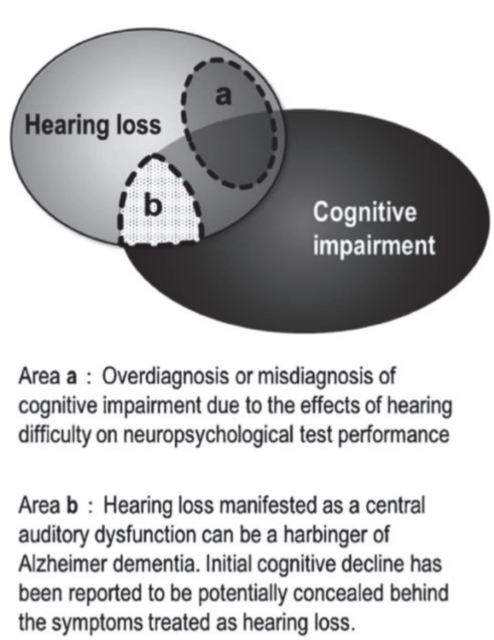

Figure 6: Overdiagnosis/harbinger hypothesis. From "Age-related hearing loss and cognitive decline – The potential mechanisms linking the two", by Uchida et al., 2019, *Auris Nasus Larynx, 46*(1), 1-9. Copyright granted 2019 by Elsevier B.V.

1.2.4.2 The association between hearing loss and cognition

The association between cognition and hearing loss and its underlying mechanisms have been widely researched. Lin et al. (2013) conducted a prospective study looking into the older adult population, investigating whether hearing loss and cognitive decline are independently associated by measuring both hearing and cognition for more than six years. Participants were required to perform two cognitive tests – Modified Mini Mental State Examination (3MS) and Digit Symbol Substitution Test. These two tests examine participants' global functioning, i.e. orientation, language, memory, concentration, and executive functioning, i.e. attention and working memory. Results showed that participants with hearing loss had a higher risk of cognitive decline than those with normal hearing.

Lin and colleagues suggested that the results obtained from their study could contribute to three hypotheses that were discussed in Uchida et al. (2019). Firstly, as suggested in overdiagnosis hypothesis, many cognitive assessments rely heavily on the individual's ability to hear test instructions, placing those with hearing loss at a disadvantage. This therefore may have caused a bias towards their results. Furthermore, as suggested in cascade hypothesis the fact that individuals with hearing loss may experience social isolation which leads to higher risk of cognitive decline, Lin et al. (2013) discussed that this hypothesis might have contributed to their results. Finally, it was suggested that hearing loss may be associated with cognitive decline possibly through cognitive load. This is related to the cognitive load theory where effortful listening could cause brain structural changes and neurodegeneration in individuals with hearing loss, and also require more cognitive resources in auditory processing thus resulting in cognitive overload.

Loughrey et al. (2018) investigated the association between age-related hearing loss and higher risk of cognitive decline through a meta-analysis. In this study, a significant association between age-related hearing loss and a higher risk of having cognitive decline was found, providing further evidence towards hearing loss as a risk factor towards cognitive decline. Loughrey and colleagues also suggested that the results obtained could attribute to the cascade hypothesis – "use it or lose it" theory, where prolonged hearing loss could result in brain atrophy due to lack of auditory stimulation.

From the findings suggested by Lin et al. (2013) and Loughrey et al. (2018), it could assume that hearing loss and cognitive decline occur simultaneously due to ageing factors. This arises from the fact that both studies investigate older adult participants with age-related hearing loss. Age has also been found to have a relationship with both cognitive decline and hearing loss (Wilson et al., 2002; Wang & Puel, 2020). Wilson and colleagues examined the changes in older adult participants over 6 years using a battery of cognitive tests. The results suggest that as age increases, cognitive ability tend to decline with poorer working memory (Wilson et al., 2002). Furthermore, Wang and Puel (2020) suggested that as age increases, the risk of hearing loss increases. This therefore suggests that age plays a factor for the relationship between cognition and hearing loss.

On the other hand, Welch and Dawes (2007) investigated cognitive ability, linguistic ability, speech intelligibility in noise, and behaviour in children with normal hearing. It was found that those with better hearing (when compared 0dB HL with 15 dB HL) performed better in general, except better behaviour was found in females and not in males. The results of their study also showed that the relationship between cognition and hearing loss found in other studies such as Lin et al. (2013) in older adult population occurs in the young population as well. Welch and Dawes (2007) therefore proposed that age might not be the only factor contributing to cognitive decline and hearing loss to occur simultaneously.

Füllgrabe, Moore, and Stone (2015) aimed to investigate whether aging contributes to reduced speech intelligibility. Normally-hearing adult participants were recruited from different age groups, where Füllgrabe and colleagues matched older normal-hearing participants (aged 60-79 years) with younger normal-hearing participants (aged 18-27 years) based on hearing thresholds, education level, and performance IQ. It was found that speech identification was lower in older participants than in younger participants as well as cognitive ability. A positive correlation was found between these two factors (i.e cognitive ability and speech identification scores). It was also found that cognitive decline can occur with aging even in the absence of hearing loss. Therefore, Füllgrabe et al. (2015) suggested that poorer speech perception in older adults is somewhat related to cognitive decline, however not causative of each other. Cognitive decline can also occur without the presence of hearing loss.

Another study that was done by Jafari, Kolb, and Mohajerani (2019) studied the diverse interactions among age-related hearing loss, tinnitus, cognitive decline in older adults, and the outcome of hearing amplification with age-related hearing loss and cognitive decline. It was concluded that although cumulative evidence has been found in identifying a link between hearing loss and cognitive decline, little mechanistic causal evidence has yet to be discovered, thus suggesting more future research is needed to clarify the relationship between the two factors.

1.2.4.2.2 Current research

In Phase 1 of the current research, the effect of the presentation modality of cognitive assessment on working memory performance was investigated between different hearing groups – cochlear implant users, individuals with severe-profound hearing loss, and individuals with normal hearing. Working memory was assessed using Digit Span and Arithmetic subtests from the Wechsler Adult Intelligence Scale IV (WAIS-IV), presented in both auditory and visual modalities. The results from Phase 1 showed that the Digit Span task appeared to be easier through auditory than visual modality across all hearing groups. On the other hand, in Arithmetic task, cochlear implant users performed better in visual than in auditory modality. No significant difference was found in other hearing groups' performance across modalities.

1.2.5 Can cognitive decline be reduced by treating hearing loss?

1.2.5.1 Hearing aids

Hearing aids have been one of the most common interventions for hearing loss as they are non-invasive and more economical than other assistive devices such as cochlear implants (Chisolm et al., 2007). Its effectiveness in reducing the barriers contributed by hearing loss has also been widely researched. However, with the increasing focus on the association between hearing loss and cognition, researchers have been looking into the relationship between hearing aid use and cognition. The common question being asked is: are hearing aids beneficial in preserving cognition in the older adult population with hearing loss?

There has been some evidence regarding hearing aid use having a positive effect on cognitive performance in older adults with hearing loss (Allen et al., 2003; Choi et al., 2011; Desjardins, 2016; Doherty & Desjardins, 2015; Mulrow, Tuley, & Aguilar, 1992).

Desjardins (2016) was one of the studies examining the relationship between hearing aid use and cognition. The effect of hearing aid use among older adult participants was investigated, and cognitive test was done before, during, and after the use of hearing aids over 6-month period. Results showed that all participants improved significantly in cognitive test with hearing aid use, where the test measures involve working memory and selective attention. Furthermore, it was found that as participants stopped using hearing aids two weeks after the 6-month period, participants' cognitive performance returned to baseline levels. Most of the participants did not show improvement in auditory processing tasks.

Desjardins (2016) therefore concluded that the study findings support the hypothesis that hearing aid use could improve cognitive performance. Besides, the findings also support the idea proposed in the cognitive load hypothesis (Uchida et al., 2019). As the cognitive load hypothesis proposed that hearing loss results in effortful listening due to degraded signals, and thus individuals with hearing loss require more attention and cognitive resources to understand speech, which leads to excessive cognitive load. With excessive processing in everyday life this therefore could further lead to changes in brain structures, and hypothetically could face cognitive decline. With hearing aid use, the amplification from the device allows individuals to require less working memory and auditory processing in speech therefore reducing cognitive load. This could then result in less effortful listening with improved attention and working memory functions.

With the results showing participants' cognitive performance returned to baseline levels after stopping hearing aid use, this could contribute to the overdiagnosis hypothesis where most cognitive assessments rely on verbal memory, therefore putting those with hearing loss at a disadvantage. This also reflects that hearing aids are able to provide compensation at auditory level and immediate effect on improving working memory and selective attention, however might not contribute to improvement in some other cognitive aspects.

Choi et al. (2011) investigated if hearing aid use in older adults can lead to an improvement in speech-related cognitive function and speech-in-noise intelligibility. Choi and colleagues compared cognitive and speech performance between the aided and unaided groups at baseline and after six months. Results showed that the aided group improved significantly in short-term memory and learning ability after six months of hearing aid use, however no significant difference was found in speech-in-noise intelligibility. It was therefore concluded that hearing aid use could result in improvement of speech-related cognitive performance and also may induce neuropsychological changes (Choi et al., 2011).

The results from Choi et al. (2011) support the cascade hypothesis where sensory deprivation could affect cognition functioning. With hearing aid use, this could restore sensory input therefore leading to improvement of cognitive function which was shown in the study findings.

Dawes et al. (2015) carried out a longitudinal study to investigate hearing aid use and its long-term outcomes such as cognitive performance, social engagement, mental and physical health in older adults over a period of 11 years. These outcomes were measured using several test batteries to assess each outcome such as Hearing Handicap Inventory for the Elderly (HHIE-S), and cognitive test, Mini Mental State Examination (MMSE). MMSE is a screening tool to identify the presence of cognitive impairment, commonly used by health professionals to screen for dementia. These assessments were carried out before, during (5 years after baseline), and after (11 years after baseline) hearing aid use. No significant difference was found between those with hearing aids and those without, in cognitive performance, social engagement, and mental health. However, findings showed that those who were aided performed significantly better in HHIE-S compared with the unaided participants.

The study findings from Dawes et al. (2015) therefore contradict the findings in Desjardins (2016), where Dawes and colleagues concluded that hearing aids would not improve cognitive performance or prevent cognitive decline. This can be explained by the common cause hypothesis, where it was proposed that hearing loss and cognitive decline occur due to the presence of a common factor – which is responsible for age-related neurodegenerative process. In most cases of age-related hearing loss, they also portray other pathological changes; therefore Uchida et al. (2019) mentioned that age-related hearing loss and cognitive decline are multifactorial. This can include risk factors such as physical health, oxidative stress, genetics and more (Uchida et al., 2019). Therefore, then amplification of sound from hearing aids alone might not be sufficient to improve or compensate for the progressive degradation of neural connections due to aging, indicating cognition would not be affected. However, Dawes and colleagues mentioned that this study is observational; therefore the findings might not fully account for the associations observed in this study. Besides, it is also worth noting that hearing loss cannot be isolated from other variables such as level of education, socioeconomic status, and social isolation (Dawes et al., 2015).

Similarly, other studies have shown that hearing aid use over a period of six months (Tesch-Römer, 1997) and 12 months (van Hooren, Anteunis, Valentijn, & Bosma, 2005) did not result in a significant change in cognitive performance among older adults, particularly in working memory and executive function. The contradicting results from different studies on the effect of hearing aid utilization on cognition implies that the effect remains unclear therefore needing further research to investigate the long-term effects of hearing aid utilization and withdrawal effects on cognition.

1.2.5.2 Cochlear implants

While hearing aids are able to provide significant improvement in listening experience in people with hearing loss, they are unfortunately not very beneficial for those who have severe to profound sensorineural hearing loss. This is because hearing aids are devices that amplify sounds and send the amplified acoustic signals through the middle ear to the cochlea. The outcome thus relies on the responsiveness of surviving hair cells in the cochlea, while people with severe to profound sensorineural hearing loss usually have damaged hair cells.

Cochlear implants are currently the most successful prostheses for the hearing system (Völter et al., 2018). They are surgically implanted devices that can provide good speech discrimination and environmental sound awareness. They are also able to provide some discrimination of music. Cochlear implants activate the auditory nerve directly in the cochlea while bypassing the sensory transduction of inner hair cells (Møller, 2006). The outcome relies on the surviving neural elements in the cochlea. Therefore, they are used in people who have severe to profound sensorineural hearing loss caused by damage/loss of cochlear hair cells, and those who are deaf.

A cochlear implant is a prosthesis that detects, converts, codes, and transmits acoustic signals into electrical signals (Møller, 2006). The electric signals are then delivered to the cochlea. A cochlear implant consists of two components – internal and external. The internal component consists of electrode array, receiver/stimulator, and retention magnet (Diego & Maurizio, 2006). It is surgically implanted underneath the skin. The external component consists of microphone, transmitting cables, speech processor, transmitting coil, power supply, and user controls. It is worn on the head and also behind the ear.

Cochlear implant works where the microphone captures sound from the environment, followed by the speech processor that converts speech and environmental sounds to digital signals (Diego & Maurizio, 2006). The signals are then sent through the transmitting cables to the transmitting coil. The signals are received by the implant underneath the skin where they are converted into electrical signals. The electrical signals are thendistributed across the electrode array, where the auditory nerve fibres in the cochlea are stimulated (Diego & Maurizio, 2006). The stimulation of auditory nerve fibres results in the transmission of acoustic signals from auditory nerve to the auditory cortex, resulting in the interpretation of sound in the brain (Møller, 2006).

Cochlear implants are considered as more invasive and expensive than hearing aids. Therefore, cochlear implantation requires justification where patients undergo a cochlear implant evaluation process. A comprehensive assessment is carried out by an audiologist/rehabilitationist, while the surgical candidacy is determined by an Ear, Nose and Throat (ENT) surgeon. In New Zealand, public funding for cochlear implantation is provided by the Ministry of Health through the Northern

Cochlear Implant Programme (NCIP) and Southern Cochlear Implant Programme (SCIP) (Ministry of Health, 2021). The aim of the cochlear implant programme is to improve communication and quality of life of individuals with hearing loss through effective collaboration between patient and professional team. All children who fit the cochlear implantation candidacy are eligible for full public funding (Ministry of Health, 2021). The public funding however is limited for adults. In New Zealand, in order to be eligible for public funding for adult cochlear implantation, a few criteria have to be met (The Hearing House, n.d.):

(1) Patients must be New Zealand residents or citizens.

(2) Speech recognition of CVC words achieving a maximum performance-intensity (PI max) of 60% or less in the better ear.

(3) Have history of hearing aid use.

If the patient is not eligible for public funding, the patient may choose to fund privately.

If the patient meets the referral criteria, the patient will then be put on the public funding waiting list. The priority of the candidates receiving cochlear implantation depends on their level of need and potential outcomes that are assessed during cochlear implant assessment.

The benefits of cochlear implants have gained attention among researchers. Völter et al. (2018) investigated the effect of cochlear implants on cognitive performance in the older adult population. A battery of cognitive tests was used to assess different aspects of cognition such as working memory and attention at different stages – pre-implantation, 6-month, and 12-month post-implantation. Quality of life questionnaires were used in the study as well. A significant increase in cognitive performance was found at 6-month post-implantation as well as speech perception and quality of life. Long-term memory only improved after 12 months. After six months, results showed significant improvement in working memory while other cognitive functions such as attention, inhibition, short- and long-term memory, and processing speed remained stable. Therefore, it was concluded that cochlear implantation could lead to improvements in speech perception, executive functions, and quality of life.

The results from Völter et al. (2018) supported the hypothesis of continued improvement of neurocognitive processes in CI users as they climatize to the device. As a strong long-term effect of device use on cognition was found in their study, this result is different from the findings obtained from Desjardins (2016) and Dawes et al. (2015), with no positive long-term effect of device use found. This could be due to the fact that different devices were assessed, i.e. hearing aids versus cochlear implants, as well as different target population, i.e. severe-profound hearing loss individuals in Völter et al. (2018) versus mild-moderate hearing loss individuals in Desjardins (2016) and Dawes et al. (2015). With different severity of hearing loss, this could also imply that the neurological changes in the individuals could be different due to the differing quality of incoming auditory signal. For example, those with more severe hearing loss would have less auditory input therefore a possibility of greater changes in cognitive processes; however those with milder hearing loss would likely have a higher reserve of neural network due to better auditory input (Fallon, Irvine, & Shepherd, 2008). Furthermore, in Völter et al. (2018) participants who showed poor cognitive performance pre-implantation showed more improvement post-implantation than those with better cognitive performance pre-implantation. Völter and colleagues mentioned that could be due to a ceiling effect where there was no further increase in cognitive performance in participants with good pre-implantation performance.

The results from Völter et al. (2018) could contribute to several hypotheses from Uchida et al. (2018). Firstly, the improvement can be explained by the cognitive load hypothesis. The amplified auditory input provided by the hearing assistive devices results in more cognitive capacity for other cognitive processes such as working memory, thus leading to a more effective bottom-up processing to occur. This is also similar to what was suggested in Desjardins (2016). Secondly, the findings could also contribute to cascade hypothesis. The long-term effect found on cochlear implant use could reflect the cascade hypothesis of reduced stimulation on damaged cochlea resulting in neuropathological changes in the brain (Uchida et al., 2018). As it was suggested that cochlear implants effectively improve auditory signals input, this implies that the auditory cortex would continue receiving stimulation therefore retaining neural connections at higher level processing (Fallon, Irvine & Shepherd, 2008).

Mosnier et al. (2015) analyzed the relationship between cochlear implant use and cognition in elderly participants. Speech perception was measured in quiet and noise settings; cognitive performance was measured using MMSE, and quality of life was assessed. Similar to Völter et al. (2018), these measures were done pre-implantation, 6-month, and 12-month post-implantation. The results were consistent with Völter et al. (2018), with more than 80% of participants showing improvement in cognition performance after 12 months. It was therefore concluded that cochlear implantation as hearing rehabilitation is associated with cognitive improvement.

Uchida and colleagues also discussed the validity of hypotheses proposed linking hearing loss and cognition and how these apply in proving hearing assistive device utilization on cognitive improvement/preservation. In Uchida et al. (2018), it was mentioned that if the cognitive load hypothesis is valid, hearing rehabilitation should result in reduced listening effort thus cognitive resources may be freed, leading to improvement in working memory. For the common cause hypothesis, the use of hearing assistive devices would not impact cognitive performance, as well as prevent cognitive decline (Uchida et al., 2018). As proposed in cascade hypothesis that deprivation of auditory input can lead to reorganization of brain structures, using hearing assistive devices would prevent the changes from occurring due to constant auditory input from the periphery (Uchida et al., 2018). Besides, the improvement of speech intelligibility from using hearing assistive devices results in an improvement in the quality of conversations, which leads to improvement in social life as well. As a result of improved quality of life, this lowers the risk of depression which may cause dementia (Hsiao, Chang, & Gean, 2018). Furthermore, Uchida et al. (2018) discussed if the overdiagnosis hypothesis is valid, the use of hearing assistive devices could separate the hearing loss factor from affecting individuals' performance in cognitive assessments and provide support for those with hearing loss (i.e. amplification of auditory input), therefore allowing them to be able to perform similarly with their normally-hearing peers. This also results in a more accurate cognitive assessment by preventing the risk of misdiagnosis or overdiagnosis of cognitive impairment.

In conclusion, the results from these previous studies have been inconsistent. The reason behind hearing assistive device utilization to prevent cognitive decline remains unclear despite researchers claiming an association between hearing loss and cognitive decline. Therefore, further research with larger sample sizes, especially randomized control trials and longitudinal studies, is needed to determine the long-term effect of hearing assistive device use. This is because the age-related cognitive decline is a slow progress; thus the short-term effect of hearing assistive device use has lower validity in preserving cognition (Uchida et al., 2018).

C h a p t e r   2

CURRENT RESEARCH AND AIMS

2.1 Current study

The goal of the current study (Phase 2) aims to continue exploring the potential relationship between hearing loss and cognition in the older adult population that has been investigated in Phase 1 of the study, with the aims and associated hypotheses mentioned below.

In Phase 1, no hearing loss simulation was carried out, therefore in the current study (Phase 2) two hearing loss simulation groups were added. This aims to investigate further how hearing loss could be associated with cognitive decline by isolating the hearing loss factor itself through simulation. While previous studies have explored different simulation methods, the current study seeks to carry out a similar method, i.e having a competing stimuli e.g speech noise to target stimuli such as sentences, but with a simpler set up.

Our aim is to simulate a cochlear hearing loss, to a severe extent, which is often accompanied by elevation of audiometric thresholds due to damage to the outer/inner hair cells, and to investigate whether cochlear hearing loss could have an impact on cognitive performance. This is done by comparing the performance difference in a cognitive test between participants with normal hearing and normal-hearing participants with a hearing loss simulation, with similar cognition in both groups. This could also further contribute to the potential association between cognition and hearing loss, relating to the overdiagnosis hypothesis or cognitive load hypothesis – however this requires further research to be done to obtain more robust evidence. As there are several ways to simulate a cochlear hearing loss, it has been mentioned in previous studies that there is not a perfect simulation method to achieve all the effects of cochlear hearing loss due to the lack of homogeneity among individuals with cochlear hearing loss.

In this current study, we aimed to simulate several aspects of sensorineural hearing loss, to a severe extent, such as reduced frequency resolution, loudness recruitment, and elevated thresholds. However, due to limited resources and a shortened period of research set up due to COVID-19 outbreak in Auckland, New Zealand in 2021, this resulted in adjustments in research work; therefore, a simpler set up of hearing loss simulation was used in this study.

2.2 Aim One: To investigate the effect of hearing loss simulation on cognitive performance on individuals with normal hearing.

Hypothesis 1: Normally-hearing participants with hearing loss simulation would show poorer performance in cognitive assessment tasks (i.e Digit Span and Arithmetic from Weschler Adult Intelligence Scale IV) than normally-hearing participants without hearing loss simulation in auditory modality.

Poorer performance in auditory modality among normally-hearing participants with hearing loss simulation can be explained by the cognitive load hypothesis where hearing loss could result in more cognitive resources being used for auditory processing. This leads to excessive cognitive loading therefore impacting on working memory and attention, which are one of the important aspects for cognitive assessment especially in Digit Span and Arithmetic tasks.

Furthermore, a poorer performance is expected from those with hearing loss simulation even though both groups have normal hearing therefore similar cognitive abilities is expected as well. This can be explained by the overdiagnosis hypothesis, where cognitive impairment is being misdiagnosed/over diagnosed due to cognitive assessments heavily relying on verbal instructions. With hearing loss simulation as a barrier for the normally-hearing participants, this puts them at a disadvantage therefore a poorer performance would be expected. However, both groups would be expected to perform similar in visual modality due to the absence of reduced auditory input.

Hypothesis 2: Normally-hearing participants with hearing loss simulation would perform better in cognitive assessment tasks in visual modality than participants with severe-profound hearing loss but similar performance in auditory modality.

This hypothesis is aiming to contribute evidence to cognitive load hypothesis and also looking into the effectiveness of hearing aids in restoring cognition in people with hearing loss. Normally-hearing participants with simulated hearing loss would be expected to perform similarly to those with severe-profound hearing loss in auditory modality due to the reduced auditory input from the simulation to a severe level. Besides, those with severe-profound hearing loss would not be wearing their hearing aids during the tasks, therefore effortful listening would occur with the absence of hearing aid amplification. This could also explain the immediate effect of hearing aid use.

On the other hand, normally-hearing with simulated hearing loss would perform better in visual modality than those with severe-profound hearing loss. This is proposed from the idea of global impact of hearing loss on cognitive decline which has been proposed in Lin et al. (2011b) and Lin and Albert (2014). It was suggested in those studies that hearing impairment is independently associated with accelerated cognitive decline. This also allows further exploration on the long-term effect and protective effect of hearing aids on cognition, since studies have found inconclusive results on hearing aid use in prevention of cognitive decline.

2.3 Aim Two: To investigate how the different sensory modality could have an impact on cognitive performance on individuals with different hearing levels.

Hypothesis 3: Participants with severe-profound hearing loss and hearing loss simulation would perform better in visual modality than auditory modality, but not those with normal hearing and CI users which they will perform similar across both modalities.

Similar to Hypothesis 1 and 2, poorer performance in cognitive assessment tasks would be expected in auditory modality among participants with severe-profound hearing loss and simulated hearing loss due to cognitive load hypothesis and could therefore potentially contribute to overdiagnosis hypothesis as well. Individuals with normal hearing should be expected to perform similarly across both modalities due to good cognition and the absence of hearing loss as barriers when executing tasks. CI users would also be expected to perform similarly in both modalities due to the recovery effect from cochlear implantation.

2.4 Aim Three: To investigate the potential effect of hearing loss on cognitive performance.

Hypothesis 4: Participants with normal hearing and those with cochlear implants (CI), on average, will perform better in cognitive assessment tasks than participants with severe-profound hearing loss and those with hearing loss simulation.

The poorer performance of participants with severe-profound hearing loss could explain the global impact of long-term hearing loss on cognition due to auditory deprivation. This could also explain the overdiagnosis hypothesis where individuals with hearing loss are being put at a disadvantage in cognitive assessments due to reduced auditory input, leading to misdiagnosis or over diagnosis of cognitive impairment. This also applies to those with hearing loss simulation in the auditory modality. The poor performance among those with severe-profound hearing loss and simulated hearing loss could support the proposed idea of limited working memory capacity from effortful listening in cognitive load hypothesis.

C h a p t e r 3

METHODS

The methods were approved by the Auckland Health Research Ethics Committee (AHREC) on 14th October 2021 for a period of three years (Reference number AH22816). All testing and data collection were administered by the student researcher, at Building 507 at the University of Auckland Grafton Campus Hearing and Tinnitus Clinic.

3.1 Participants

Participants were allocated into five different groups: cochlear implant users (CI), people with severe-profound hearing loss who are on the cochlear implantation waiting list (WL), people with normal hearing (NH), and two groups of people with normal hearing with simulated hearing loss, SHL70 and SHL60.

Participants from the CI group and WL group were recruited from the Adult Northern Cochlear Implant Programme (NCIP), where invitation emails were sent to patients on the clinical database, through clinician's referral and poster advertisement. Advertisement posters were posted on noticeboards at the University of Auckland Grafton Campus to recruit people with normal hearing for the NH group and SHL groups. Those interested in participating in this study were required to contact the student researcher via email. An invitation pack consisting of invitation letter, participant information sheet, and consent form was sent out prior to appointment and also during the appointment.

The inclusion criteria for this study include all participants who fall into the older adult population, i.e. 40 years and above, are fluent speakers of English, no significant visual impairment and self-reported no known cognitive difficulties. The participants in CI group were required to have worn cochlear implants for six months and above. This is to ensure that the participants have had a sufficient amount of time and experience with wearing the device and getting used to the sounds. The participants in NH and SHL groups were required to have self-reported normal hearing. Participants were required to come to the university for the testing. Participants who did not meet the selection criteria were excluded. Ten participants were intended to be recruited for each group for a total of 50 participants.

Ten participants were successfully recruited for the NH group and SHL70 group. However, only 4 participants were managed to be recruited for the SHL60 group; 1 participant each in CI and WL groups were recruited. This results in a total of 26 participants recruited for the current study. This was due to the current Delta and Omicron outbreaks across New Zealand, which severely impacted the process of participant recruitment. As the virus remains infectious in the community, the campus has remained closed to students and the public since 2021. This therefore resulted in no access to clinic for research, and while this study targets the older adult population, this also impacted on participant recruitment while the elderly population remains vulnerable to the virus.

As a hearing screening was carried out in the NH group and SHL groups before conducting the study, the participants in those groups had an average hearing threshold of 15dB HL. In CI and WL groups, all participants had severe to profound hearing loss as they would have met the eligibility criteria for NCIP, either for cochlear implantation or candidacy on the waiting list. The hearing levels in NH, CI, and WL groups from Phase 1 of the study are the same in the current study (Phase 2); therefore data from both phases were combined, analyzed, and discussed together in this study.

3.2 Procedure

Participants were required to attend a one-off session of testing which took up 1 hour, including rest breaks if needed. At the start of the testing session, all participants were given a participant information sheet and consent form. A debrief was given regarding the tasks that the participants were required to carry out during the testing. Informed written consent was obtained from all participants prior to testing. All participants were required to complete two cognitive subtests of the Wechsler Adult Intelligence Scale IV (WAIS-IV) – digit span task and arithmetic task. Both subtests were carried out twice in different modalities, once through visually and once through verbally. All participants have also been asked a few questions to obtain demographic information (date of birth, age, sex) across all groups, duration and onset of hearing loss in CI and WL groups, and duration of cochlear implantation in the CI group. A quick hearing screening was done for the participants in NH and SHL groups prior to testing to ensure that their hearing thresholds fall into the normal range (15dB HL).

For participants in the CI group and WL group, informed written consent was obtained in order for the researchers to access their existing hearing data from the clinical records. All participants were reimbursed with a $10 voucher for their participation in the research at the end of the session.

3.3 Cognitive assessments

Wechsler Adult Intelligence Scale IV (WAIS-IV) is a test designed for clinicians to measure cognitive ability in adults. This test is most commonly used among individuals aging 16 years to 90 years and 11 months. Two subtests will be used in this study in this assessment – Digit Span and Arithmetic tasks. These two subtests are able to assess an individual's ability to process the information given by the student researcher in immediate awareness, followed by mental operation of the information.

3.3.1 Digit span task

The Digit Span task in WAIS-IV consists of 3 different subtasks – Digit Span Forward, Digit Span Backward, and Digit Span Sequencing. This test measures working memory, auditory recall, and short-term memory.

The participants were presented with a series of digits of increasing length, ranging from 3 to 9 digits. Participants were required to repeat the digits back to the examiner in the same order as presented in Digit Span Forward e.g. "3-6-2"; in reversed order in Digit Span Backward e.g. "2-6-3"; and in ascending order in Digit Span Sequencing e.g. "2-3-6". In all of the subtasks, each sequence of digits could only be presented once; no repeats were allowed. A point is given if the participant provides a correct response, while the participants would score 0 points if an incorrect response is given. No points would be given if the participants reported that they did not know the answer, or no response was given in 30 seconds. All subtasks were discontinued after scores of zero on both trials of an item – which means when the participants failed to repeat two sequences of digits of an item.

The Digit Span task was carried out twice for each participant – once in the auditory modality and once in the visual modality. Different sets of test items were used for each modality to prevent participants from learning the test items. In the auditory modality, the researcher sat across a table approximately one meter away from the participant. The researcher carried out the task as usual, where the participants would be able to hear the researcher as well as seeing the researcher's face. However, in the visual modality, the participants were seated approximately 1 meter in front of a computer monitor. All sequences of digits were presented on the computer screen with one digit presented at a time with a 1-second interval between each digit, followed by a blank screen. The participants were instructed to provide their answers only when the blank screen was presented.

The tasks were carried out in the same method across all participants group, except where in the SHL group the participants were under a simulated hearing loss with earphones inserted.

3.3.2 Arithmetic task

The Arithmetic task involves the participants mentally solving a series of arithmetic problems. This test assesses working memory, calculation skills, problem-solving skills, and mental manipulation of number operations.

All arithmetic problems were presented in word form. For example, the researcher would present a problem verbally: "Louis has six books. He lost three books. How many books does Louis have left?". The participants were given 30 seconds to solve each problem, where the timing starts at the end of each question. No calculators or pen and paper were allowed during this task however participants were allowed to use their fingers to solve the problem. Each problem could be repeated once if required. A point is given for every correct response provided within the time limit. No points would be given if an incorrect response was given, the participants reported that they did not know the answer, or no response was given in 30 seconds.

Similar to the Digit Span task, the Arithmetic task was carried out twice in different modalities – visual and auditory. Different sets of test items were used for each modality, with the same difficulty level and mathematical operations. In the auditory modality, the researcher sat across a table approximately 1 meter away from the participant. The researcher carried out the task it would be as usual, where the participants would be able to hear the researcher as well as seeing the researcher's face. Meanwhile, in the visual modality, the participants were seated approximately one meter in front of a computer monitor. Each arithmetic problem was presented on the screen one at a time, followed by a blank screen. The amount of time presented on screen was the same as the average time taken by the researcher to read out loud. The participants were instructed to provide their answers only when the blank screen was presented.

The tasks were carried out in the same method across all participants group, except where in the SHL groups the participants were under a simulated hearing loss with earphones inserted.

3.4 Hearing screening

A hearing screening was carried out for participants in the NH group and SHL groups prior to testing. The hearing screening was done at the University of Auckland Hearing and Tinnitus Clinic, using a Grason-Stadler Inc Audiostar Pro audiometer with the calibration due date on 11th November 2022. An air-conduction pure tone thresholds at four frequencies (500, 1000, 2000, and 4000 Hz) were screened at 15dB HL using insert earphones in a soundproof booth. The threshold-seeking method was not used as this was only a hearing screening rather than a hearing assessment. This indicates that the participants in the NH group and SHL groups could have better hearing thresholds, i.e. 15dB HL and above.

3.5 Hearing loss simulation

Hearing loss simulation was carried out in two participant groups, the SHL70 group and SHL60 group. All participants have shown normal hearing from the hearing screening. The hearing loss simulation was set up using a Grason-Stadler Inc Audiostar Pro audiometer. Speech noise was played through the insert earphones binaurally (with deep insertion achieved) while the participants remained in the soundproof booth. Otoscopy was conducted prior to ensure participants' ear canals were clear of ear wax. The speech noise on the audiometer is calibrated in effective masking level and contains a spectrum of equal energy per frequency from 100Hz to 1kHz with a 12dB/octave roll-off from 1k to 6kHz (Grason-Stadler, n.d.). The noise was played at 70dB HL in the SHL70 group and 60dB HL in SHL60 group. The study was then carried out with the noise playing through inserts throughout the tasks.

A sound level meter was used to measure the sound level of the student researcher's voice when reading out instructions and task problems of the cognitive tasks used in this study. This provides an approximate way of how loud the voice would sound to participants' ears and gives an objective measurement of sound pressure levels. The C-DSM1 Handheld Digital Sound Level Meter was used to measure the sound level of the student researcher's voice. The sound level meter was placed in between the student researcher and participant, approximately 0.5 metre away from the student researcher as both student researcher and participant were sitting 1 metre apart. An average voice level of 55dB was obtained. 70dB HL was decided for the speech noise level to achieve a signal-to-noise ratio (SNR) of -15dB. The goal of SNR -15dB is to create a better imitation of a more severe hearing loss, however participants would still be able to retain some of their speech intelligibility during the tasks. Before adding another hearing loss simulation group at 60dB HL, different levels were trialed with different volunteers, and 60dB HL appeared to be the most suitable simulation level after the 70dB HL option for a few reasons. Firstly, the 60dB HL simulation aimed to continue simulating a sensorineural loss to a severe extent however since the average voice level is at 55dB, a simulation at 50dB would not be suitable for a hearing loss simulation at a severe level. Besides, 70dB HL appeared to be the tolerance level of most volunteers; therefore a higher simulation level would not be appropriate as well.

3.6 Data analysis and management

Due to the restrictions in time and resources imposed by a Master's thesis, and with the added impact of the response to the Covid-19 pandemic, it was not possible to collect all the data to compare people with severe-profound hearing loss with and without cochlear implantation, and normally-hearing people with and without simulated hearing loss in one year. Therefore, the research was divided into two phases, Phase 1 and Phase 2, which followed the same methods and used identical procedures. The data obtained during Phase 1 were combined with the data collected in the current study (Phase 2) during data analysis. This provides greater statistical power as the sample size increases.

The scores for the hearing groups were inspected visually to check for outliers or non-normal distributions. The group with simulated 60dB HL (SHL60) was relatively small, with four participants, and the scores appeared to be bi-modally distributed. An initial analysis excluding this group was therefore conducted. The bi-modal distribution could be due to the fact that it is a very small sample size with four participants, however the mean was not a good measure of central tendency because two participants performed well in the tasks but not the other two participants. This distribution might not be representative of what 60dB hearing loss simulation would present in normal hearing participants, so the data from the SHL60 group were therefore excluded in further analysis of data.

Mauchley's test of sphericity was used to assess the assumption of sphericity in the data in the analysis. No effect was significant, implying that the data met this assumption.

The Digit Span and Arithmetic raw scores obtained from participants in each group were converted into scaled scores as stated in WAIS-IV. The data were then entered into IBM SPSS statistical software. A two-way ANOVA was carried out to investigate the effect between hearing groups, modality, and test.

A comparison was first made between the NH groups from Phase 1 and Phase 2 of the study. This was done to ensure the comparability between the techniques used in Phase 1 and Phase 2, where the methods used were consistent throughout both phases. This also ensures both data were confident to be combined for analyses.

The table below shows the statistics done from both NH groups in each phase (Table 3). The mean test scores were compared. T-tests were also carried out to determine if any small differences were significant ($p<0.05$), as shown in Table 4. Findings showed the differences between the two groups were not significant, indicating the techniques used in both phases were consistent; therefore both data could be combined.

	Group	**N**	**Mean**	**Standard deviation**	**Standard error mean**
DS Scaled (A)	Phase 1	11	10.27	3.26	0.98249
	Phase 2	10	10.50	2.22	0.70317
A Scaled (A)	Phase 1	11	11.09	3.24	0.97659
	Phase 2	10	11.10	5.92	1.87053
DS Scaled (V)	Phase 1	11	9.27	1.90	0.57352
	Phase 2	10	9.80	2.44	0.77172
A Scaled (V)	Phase 1	11	11.09	3.24	0.97659
	Phase 2	10	13.30	3.71	1.17426

Table 4: Average, total sample size, standard deviation, and standard error mean of NH groups from each phase (Phase 1 and Phase 2) in Digit Span (DS) and Arithmetic (A) tasks in each modality (Auditory or Visual).

	t	df	Mean of Phase 1	SD of Phase 1	Mean of Phase 2	SD of Phase 2
DS Scaled (A)	0.185	19	10.27	3.26	10.50	2.22
A Scaled (A)	0.004	19	11.09	3.24	11.10	5.92
DS Scaled (V)	0.555	19	9.27	1.90	9.80	2.44
A Scaled (V)	1.456	19	11.09	3.24	13.30	3.71

Table 5: t-tests to compare mean test scores in NH groups from each phase (Phase 1 and Phase 2) for any significant small differences ($p<0.05$) in each test, Digit Span (DS) and Arithmetic (A) in each modality (Auditory and Visual). t: t-value, df: Degrees of freedom, SD: Standard deviation.

Chapter 4

RESULTS

A two-way ANOVA was conducted to investigate the effect of different sensory modalities (Auditory or Visual) on the performance in both Digit Span and Arithmetic tasks across all hearing groups. The Digit Span and Arithmetic tasks scores were converted to scaled scores obtained from WAIS-IV. To obtain the scaled scores for each test in WAIS-IV, the raw scores are summed and then converted to scaled scores. The sum of scaled scores is then computed for the core subtests, then converted to a standard score (Wechsler, 2008). According to participants' age groups, the scaled scores were obtained from the appendices in WAIS-IV. The scaled scores were then averaged to obtain the mean test scores. A table showing descriptive statistics of each test in both modalities across all hearing groups is also shown below (Table 5).

	Hearing groups	N	Mean	Standard deviation
DS Scaled (A)	Severe-profound HL	11	9.55	3.36
	Simulated 70dB HL	10	4.90	3.11
	CI	12	10.00	2.59
	Normally-hearing	21	10.38	2.75
	Total	54	9.11	3.49
A Scaled (A)	Severe-profound HL	11	9.82	3.87
	Simulated 70dB HL	10	5.10	2.77
	CI	12	10.50	3.48
	Normally-hearing	21	11.10	4.58
	Total	54	9.59	4.41
DS Scaled (V)	Severe-profound HL	11	8.36	3.26
	Simulated 70dB HL	10	8.70	1.49
	CI	12	9.00	2.73
	Normally-hearing	21	9.52	2.14
	Total	54	9.02	2.42
A Scaled (V)	Severe-profound HL	11	10.45	3.39
	Simulated 70dB HL	10	13.60	2.67
	CI	12	12.08	2.15
	Normally-hearing	21	12.14	3.57
	Total	54	12.06	3.18

Table 6: Descriptive statistics (total sample size, mean test score, and standard deviation) of each test in both modalities (Auditory and Visual) across all hearing groups.

The data from each test, Digit Span and Arithmetic, were analyzed separately. This is to obtain a more explicit result of participants' performance in each test presented in two different modalities, as these two tests measure different aspects of cognitive processes.

In Digit Span, there was a significant interaction between the modality of the test and hearing groups (F $(3,50)=10.665$, $p<0.001$).

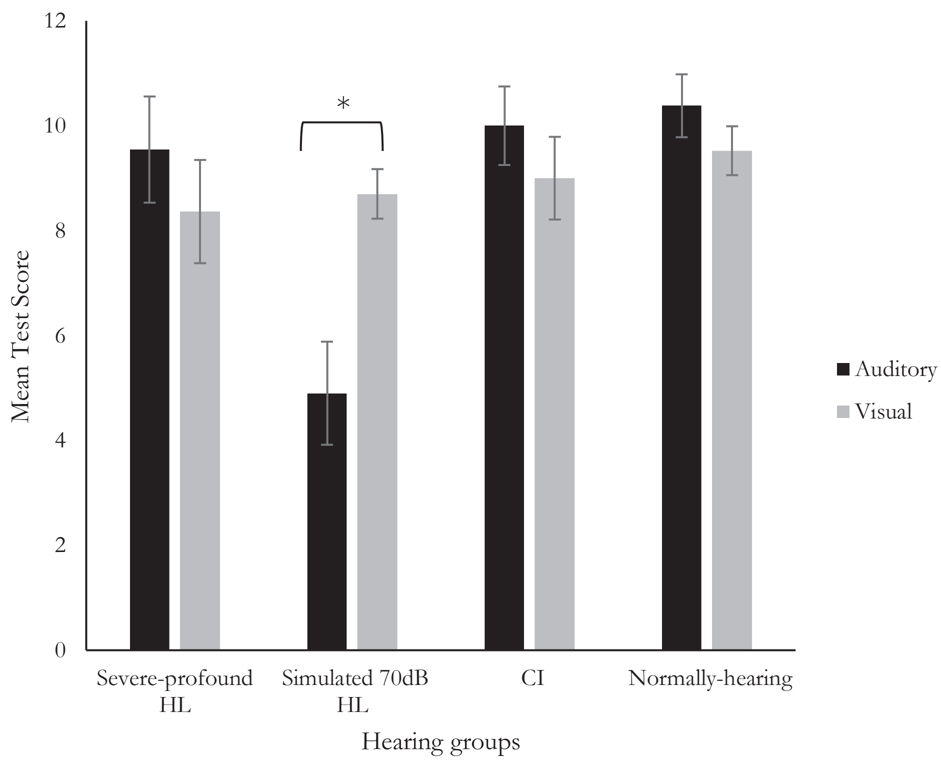

Figure 7: Mean test score in Digit Span task across all hearing groups, in Auditory and Visual modalities. Error bars indicate the standard error of mean test score. *$p<0.001$

Figure 7 shows that all participants across all hearing groups performed better in auditory (black bars) than in visual modality (grey bars), except the SHL70 group.

There is a huge difference in performance in the SHL70 group in different modalities, however this could be due to the very low performance of the SHL70 group in the auditory modality, hence showing the vast difference. Besides, as all participants appeared to perform similar across all groups in both modalities (except SHL70 in auditory modality), this could indicate that there does not appear to be much cognitive difference among the participants across the hearing groups.

Furthermore, in the Arithmetic task, there was an interaction between modality and groups (F (3,50)=19.696, p<0.001) shown in the graph below.

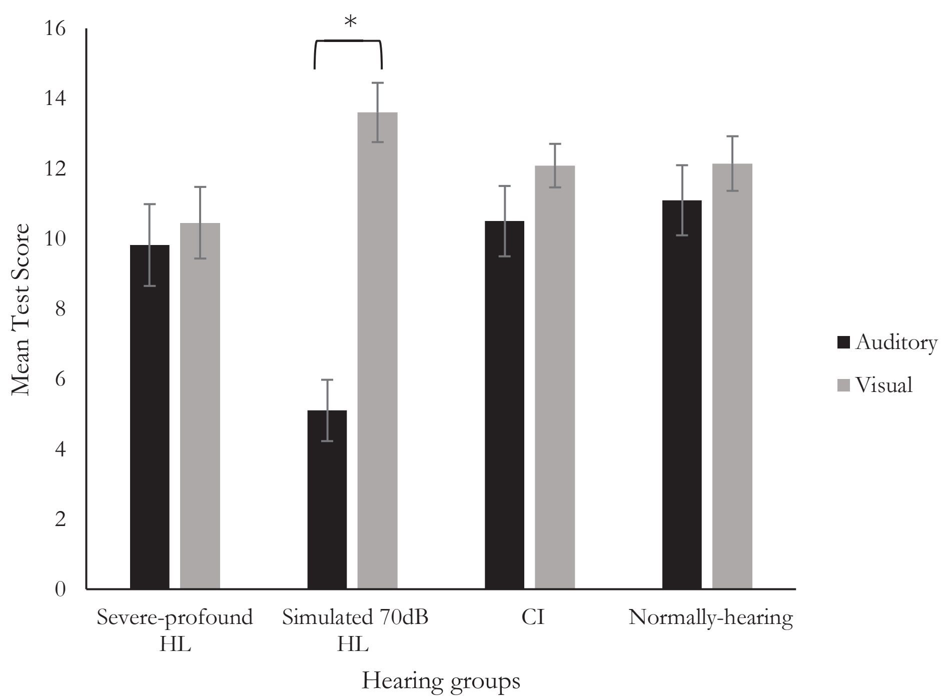

Figure 8: Mean test score in Arithmetic task across all hearing groups, in Auditory and Visual modalities. Error bars indicate the standard error of mean test score. *p<0.001

Figure 8 shows that all hearing groups performed better in visual modality than in auditory modality for the Arithmetic task. Similar to the Digit Span task, a huge difference was found in the SHL70 group between both modalities. Again, this could be due to the very low performance of the SHL70 group in the auditory modality. Overall, i.e. the average taken across the two modalities, there was no significant difference in performance between the hearing groups with the significance level of p=0.272. Therefore, this could also rule out the effect of sensorineural hearing loss on cognitive performance.

C h a p t e r   5

DISCUSSION

In this chapter, a summary of the results will be presented in relation to the aims and hypotheses of the current study. This will then follow with a discussion of the results as well as the strengths and limitations of this study. Clinical implications of the findings of this study will be discussed as well.

5.1 Summary of results

From the findings of the current study, there was a significant interaction between hearing groups and modality in both Digit Span and Arithmetic task. In the Digit Span task, all hearing groups performed better in auditory modality than visual modality, except the SHL70 group. In the Arithmetic task, all hearing groups performed better in visual modality than in auditory modality. It was also observed that the SHL70 group performed poorly in auditory modality across both Digit Span and Arithmetic tasks.

5.2 Aim One

The first aim of the current study was to investigate the effect of hearing loss simulation on cognitive performance in individuals with normal hearing, which was not explored in Phase 1 of this research.

5.2.1 Hypothesis 1: Normally-hearing participants with hearing loss simulation would show poorer performance in cognitive assessment tasks (i.e Digit Span and Arithmetic from Weschler Adult Intelligence Scale IV) than normally-hearing participants without hearing loss simulation in auditory modality.

In relation to Hypothesis 1, normally-hearing participants with hearing loss simulation did show poorer performance in cognitive tasks (both Digit Span and Arithmetic tasks) than those without hearing loss simulation in the auditory modality. This can be seen in Figure 7 (Digit Span) and Figure 8 (Arithmetic). In fact, the hearing loss simulation group (SHL70) showed the lowest performance across all other hearing groups in the auditory modality across both tasks.

The mean test scores that have been converted into scaled scores according to different age groups in Digit Span and Arithmetic tasks were compared across all hearing groups between auditory and visual modality. In auditory Digit Span (Figure 7), the SHL70 group scored the lowest while the other groups (CI, WL, and NH groups) performed similarly, with the NH group scoring slightly higher than CI and WL groups. A similar trend was found in the Arithmetic task as well, in the auditory modality (Figure 8).

This finding can be explained by the cognitive load hypothesis by Uchida et al. (2018), where effortful listening reduces cognitive resources for other cognitive processes. This therefore leading to poor working memory, as shown in poor results obtained in Digit Span and Arithmetic, which assess working memory in WAIS-IV. As the participants in SHL70 performed the tasks with a hearing loss simulation (i.e. speech noise playing through inserts), this resulted in reduced audibility; therefore, more listening effort such as attention and concentration would be needed to understand instructions and tasks during the study. On the other hand, the NH group did not face this barrier of reduced audibility during the tasks. This indicated that more cognitive capacity could be used for attention and working memory. This resulted in better scores in the assessment than those with hearing loss simulation, even though both groups have similar cognitive abilities.

5.2.2 Hypothesis 2: Normally-hearing participants with hearing loss simulation would perform better in cognitive assessment tasks in visual modality than participants with severe-profound hearing loss but similar performance in auditory modality.

In Hypothesis 2, the goal was to investigate not only the immediate effect of hearing impairment on cognition, but also the long-term effect of hearing impairment on cognitive abilities. As proposed in the cognitive load hypothesis, excessive cognitive load from effortful auditory processing would result in limited working memory; and in the long run, this would also lead to brain structural changes. This also overlaps with the idea proposed in the cascade hypothesis. Cascade hypothesis proposed that auditory deprivation could lead to neuropathological changes in the brain due to lack of stimulation (Uchida et al., 2018).

If the cognitive load hypothesis is valid, the participants in the SHL70 group will perform similarly to participants in the WL group in the auditory modality due to effortful listening, as the WL group would have carried out the task without hearing aids. Interestingly, participants in the WL group performed significantly better than the SHL70 group in the auditory modality across both tasks, and both groups performed similarly in the visual modality.

On the other hand, the finding could potentially contribute to the cascade hypothesis. As those with severe-profound hearing loss in the WL group would have worn hearing aids for an extended period, the amplification from hearing aids provided auditory stimulation at the periphery level could have prevented loss of neural connections in the auditory cortex – which was proposed in the cascade hypothesis linking the association between hearing loss and cognitive decline. This could also provide evidence of hearing aid use in the prevention of cognitive decline, as stated in Lin (2012) and Desjardins (2016). The long-term protective effects of hearing aid use from cognitive decline could also be seen when comparing the mean test scores between the WL group and SHL group in the visual modality. Both groups performed similarly in the visual modality, indicating that participants in both groups have similar cognitive abilities, even though the WL group has long-term hearing loss. If the proposed idea of the global impact of long-term hearing loss on cognitive performance is valid, which was mentioned in Lin et al. (2011) and Lin and Albert (2014), the WL group would be expected to perform worse than the SHL group in both modalities and not just in the auditory modality.

5.3 Aim Two

The second aim of the current study was to investigate the effects of different sensory modalities on cognitive performance across all hearing groups – severe-profound hearing loss, CI users, normally-hearing individuals, and normally-hearing individuals with hearing loss simulation. This aim had also been investigated during Phase 1 of this research.

5.3.1 Hypothesis 3: Participants with severe-profound hearing loss and hearing loss simulation would perform better in visual modality than auditory modality, but not those with normal hearing and CI users which they will perform similar across both modalities.

In relation to Hypothesis 3, participants in the WL group (severe-profound hearing loss) did perform better in visual modality – however, this was only observed in the Arithmetic task (Figure 8). In the Digit Span task, the WL group performed better in auditory than in visual modality (Figure 7). Participants in the SHL70 group performed better in visual modality across both tasks, with a significant difference in mean test scores found between modalities. On the other hand, both the NH and CI groups scored better in the auditory modality in Digit Span, and visual modality in Arithmetic.

As the goal of the hearing loss simulation of the current study was to investigate the impact of the hearing loss factor itself on cognitive impairment, similar performance between the SHL70 group and WL group was therefore across both tasks. Interestingly, the findings were inconsistent with the expectation – where the WL group performed better than SHL70 group in auditory modality across both tasks. Again, this observation could contribute to the cognitive load hypothesis, as seen in the SHL70 group, where a hearing loss could result in impaired performance due to the required listening effort, leading to cognitive overload (Uchida et al. 2018).

Besides, this further explains the overdiagnosis hypothesis where individuals might present a "pseudo" cognitive impairment due to the cognitive tasks being heavily loaded for verbal skills, which would not be appropriate for those with a hearing impairment (Uchida et al., 2018). Evidence was shown in the SHL70 group's performance, where participants have normal hearing and good cognition performing poorly in both cognitive tasks in the auditory modality but not in the visual modality, under a hearing loss simulation.

The higher test scores in the WL group across both cognitive tasks in auditory modality than the SHL70 group could be explained by the hypothesis suggested by Desjardins (2016) that hearing aid use could result in an improvement in cognitive performance. This further supports the long-term protective effects of hearing aid use in Lin (2012). Furthermore, the high performance in the WL group that was similar to the performance in the NH group aligns with the hypothesis mentioned in Choi et al. (2011) that hearing aid use could result in neuropsychological changes and speech-related cognitive improvement.

The mean test scores between the WL group and CI group were very similar, and this finding could contribute evidence for not only positive effect of long-term hearing aid use but also the restorative effect of cochlear implantation. The findings were consistent with previous research by Mosnier et al. (2015) and Völter et al. (2018), where improvement in cognitive performance was observed at least six months post-implantation. The participants in the CI group were also required to have received cochlear implantation at least six months prior to study participation so that they would have gained experience in using the device and getting used to the sounds.

Furthermore, the findings from WL and CI groups could contribute to the cascade hypothesis. In the cascade hypothesis, similar to the "use it or lose it" theory, it is proposed that impoverished auditory input at the peripheral level could result in changes of brain structures such as decreased volumes in the primary auditory cortex. Conversely, with hearing assistive devices which provide amplification of auditory signals, the constant stimulation in the primary auditory cortex could prevent the reduction of volume in the primary auditory cortex.

When comparing cognitive performance across all hearing groups between the modalities in each test separately, Figure 7 showed better performance in the Digit Span task in auditory modality across all hearing groups besides the SHL70 group. This finding could contribute to the overdiagnosis hypothesis by Uchida et al. (2018), as mentioned earlier, where cognitive assessments could be inappropriate for assessing the cognitive ability of an individual with hearing impairment. This also indicated the need for some cognitive assessments to be reassessed in terms of their validity.

In Figure 8, all hearing groups performed better in visual modality of the Arithmetic task. This could indicate that the effect of hearing loss on cognitive performance could be ruled out, and the use of hearing assistive devices i.e. hearing aids and cochlear implants, might not necessarily improve cognition. However, with the WL group, CI group, and NH group showed fairly similar performance in both tasks, this could also indicate that hearing assistive devices might not necessarily improve cognition but could prevent it from declining.

The performance difference between both modalities across both tasks could be explained by several reasons. Firstly, Digit Span is a task that requires simple attention and a large working memory capacity where the participants were required to store, recall, and sequence a series of digits. For the participants in CI and NH groups carrying out tasks in the auditory modality, it would be less difficult for them as they have either good hearing or improved auditory signals from cochlear implants. According to the cognitive load hypothesis, good hearing ensured those participants remained to have sufficient cognitive capacity for attention and working memory; therefore their performance would not be affected.

In the WL group where participants have severe-profound hearing loss and were required to turn their hearing aids off during the task, it was expected that they would perform worse in auditory similar to the SHL70 group. However, the results showed an opposite outcome from the expected. The high mean test scores in the auditory modality in the WL group could be explained by the fact that the participants were relying on lip reading as they could watch the researcher's face during the task. As the digits are shorter (word level e.g. "5-7-9-0") than arithmetic problems presented in Arithmetic task (sentence level e.g. "James has four apples, he gave two away…"); and those with long-standing hearing loss would have acquired good lip-reading skills, therefore this could result in the digits were easier to be stored in working memory than arithmetic problems.

Lip reading is often used by hearing-impaired individuals during conversations as one of the communication strategies in order to improve their understanding of a conversation (Dell'Aringa, Adachi, & Dell'Aringa, 2007). This includes paying attention to facial expressions, body language, and environmental cues (Demorest & Bernstein, 1992). Blamey et al. (1989) mentioned that when hearing does not offer complete speech information, visual and tactile abilities could act as additional support with the aim of improving speech understanding. Smith and Pichora-Fuller (2015) assessed working memory in older adults with hearing loss by performing Word Auditory Recognition and Recall Measure (WARRM) auditorily and Reading Span (RS) visually. It was found that older adults with hearing loss performed better in WARRM than in RS, therefore suggesting that the monosyllabic words in WARRM could contribute to this finding as less linguistic processing was required.

Moreover, Kemtes and Allen (2008) carried out Digit Span tasks in older adults via auditory and visual modalities. The results showed better performance found in the auditory modality. It was therefore argued that verbal presentation is easier to recall due to less attentional load required than visual, suggesting a recall superiority effect (Kemtes & Allen, 2008). The findings of these studies could also explain the reason behind a better performance in Digit Span in auditory modality.

A few explanations could contribute to the Arithmetic task where better performance was observed in visual modality. Firstly, the task itself requires participants to follow the arithmetic problems presented in sentences, thus placing participants at a disadvantage, especially those in the WL group and SHL70 group. The presence of hearing loss (or simulated hearing loss) poses a barrier for those participants in processing the problems at sentence level, and this again further contributes to the overdiagnosis hypothesis. Moreover, as all participants would have to complete the tasks twice in different modalities, there is a possibility of a learning effect occurring. This is because the mathematical problems were made to have the same difficulty level and required the same mathematical operations, therefore causing an improvement in visual modality as this was carried out later than auditory modality.

5.4 Aim Three

The third aim of the current study was to investigate the potential effect of hearing loss on cognitive performance, drawing an association between hearing loss and cognitive decline in the older adult population which has been the focus of many previous research.

5.4.1 Hypothesis 4: Participants with normal hearing and those with cochlear implants (CI), on average, will perform better in cognitive assessment tasks than participants with severe-profound hearing loss and those with hearing loss simulation.

In relation to Hypothesis 4, participants in the CI and NH groups performed marginally better than the WL group in both modalities but significantly better than the SHL70 group especially in the auditory modality, as shown in Table 5. While this hypothesis aimed to explain the global impact of long-term hearing loss on cognition due to auditory deprivation, the results were inconsistent with where the WL group performed fairly similar to the CI group and NH group.

However, the findings could contribute to the overdiagnosis and cognitive load hypotheses where poor performance can be seen in the SHL70 group in the auditory modality due to limited working memory capacity to process tasks from effortful listening. This therefore shows a "pseudo" cognitive impairment contributed by reduced auditory input (Uchida et al., 2018). In addition, the good performance in cognitive tasks observed from the WL group and CI group could contribute to the effectiveness of long-term hearing assistive device use on cognition mentioned in Lin et al. (2013). While hearing loss results in less cognitive resources available in other cognitive processing due to excessive cognitive loading to compensate for auditory processing (Rabbitt, 1991), improved hearing from hearing assistive device use would result in decreased cognitive load, more cognitive capacity could be freed up, thus led to improved cognitive performance.

5.5 Strengths and limitations

The main strength of this study was the exploration of hearing loss simulation in normally-hearing individuals to investigate the impact of hearing loss itself on cognitive performance. The hearing loss simulation attempted to mimic some perceptual consequences of sensorineural hearing loss at a severe level, such as the elevation of audiometric thresholds. With this hearing loss simulation, the relationship between hearing loss and cognition could be investigated without other factors contributing to cognitive impairment.

The hearing loss simulation method used was only able to mimic some aspects of a sensorineural hearing loss, however it is known that there is still no consensus on how to simulate sensorineural hearing loss that involves different perceptual consequences. The method used in this study was to use speech noise generated from the Grason-Stadler Inc Audiostar Pro audiometer playing through inserts at 70dB HL. This could have potentially created a distraction from participants during the cognitive tasks, resulting in poor performance in the SHL70 group due to poor attention. However, by using speech noise this allowed the normally-hearing participants to experience reduced detectability of speech sounds, which reflects a huge difficulty experienced by those with sensorineural hearing loss. Furthermore, the simulation aimed to mimic a situation similar to how patients with hearing impairment taking cognitive assessment would be like, so that the potential association between hearing loss and cognition could be investigated, rather than focusing on how a sensorineural loss would 'sound' like.

Furthermore, comparing the performance of participants with simulated hearing loss and those with severe-profound hearing loss allowed more insight into the effectiveness of hearing assistive devices and the validity of cognitive assessments for individuals with hearing impairment. Besides, the findings on CI users in this current study would be able to contribute more evidence for the effect of cochlear implantation in improving hearing and cognitive ability (i.e. working memory), as there are only a few cross-sectional studies in the research field being done on this topic. While many researchers have been looking into the effect of hearing aid utilization on cognitive ability (Allen et al., 2003; Choi et al., 2011; Desjardins, 2016; Doherty & Desjardins, 2015; Mulrow, Tuley, & Aguilar, 1992), only a few studied on cochlear implantation in improving cognitive ability, such as the study conducted by Mosnier et al. (2015). Furthermore, as this study recruited participants who are 40 years old and above, this provided a more detailed insight into the potential association between hearing loss and cognitive ability in the older adult population.

There are several limitations in this study. Firstly, the small sample sizes in this study, especially in hearing loss simulation groups, SHL70 and SHL60, contributed to the lack of generalisation of the findings. A few reasons could have resulted in the small sample size in this study – this could have been due to the time constraint of this research, the shortened recruitment process, and specific participant recruitment criteria. Furthermore, the lockdown in Auckland, New Zealand that lasted for a few months during the Omicron outbreak resulted in no access to the university campus for research as it remained closed to the students and public. This contributed to a short period of time for participant recruitment and data collection. As the older adult population remained as the more vulnerable population to the virus, this also affected the process of recruitment. Having said that, any effect that was not detectable with the sample sizes taken in this study would tend to be a fairly small effect. Thus, if there were a true impact of sensorineural hearing loss effect on cognition among the participants, it would still be relatively small and not significant. Besides, the participant population that focused on the older adult population of this study also indicated that the findings limit the generalisability to the general population.

Another limitation is that the SHL60 group was excluded from data analysis due to the very small sample size, resulting in this study was not able to compare if the different levels of simulation would have contributed to a difference in participants' performance in cognitive tasks. Having said that, a comparison between SHL70 and SHL60 would be recommended in future research to determine the appropriate level of simulation for sensorineural hearing loss at a severe level.

The potential learning effect of the Arithmetic task also contributed to the limitations of this study. This is because to ensure the consistency and difficulty level of arithmetic problems in both auditory and visual modalities, the same mathematical operations were maintained in both modalities. This therefore could have resulted in better performance in the visual than in the auditory modality. To address this limitation in future research, the assessed sequence could be counterbalanced among participants. For example, some participants would start the Arithmetic task in the auditory modality while others would start with the visual modality.

5.6 Clinical implications

Increased risk of misdiagnosis or overdiagnosis among patients with hearing impairment should be taken into consideration by clinicians during cognitive assessments. Researchers should also continue investigating the validity of cognitive assessments on individuals with hearing impairment, such as creating more visual-verbal cognitive assessments to eliminate the hearing loss factor in testing (Jorgensen, Palmer, & Fischer, 2014).

As the findings in the current study supported the hypothesis of using hearing assistive devices as hearing rehabilitation (i.e. hearing aids and cochlear implants) to improve cognition or prevent from cognitive decline, this encourages clinicians and researchers to continue looking into the long-term effect of hearing assistive device use on cognition. The effectiveness of other hearing rehabilitation strategies such as cognitive training could also be investigated. The combination of both hearing assistive device use and cognitive training could show a more strengthened improvement in cognition. As both focus on improving brain plasticity, continuous exposure of cognitive and auditory inputs from training tasks and amplification of signals could result in strengthened neural networks (Lawrence et al., 2018).

While people with severe-profound sensorineural hearing loss limited benefit from the amplification from hearing aids due to the severity of the loss, cochlear implants have been the solution for these people in terms of improving speech intelligibility and restoring social life and confidence. The current study's findings showed that cochlear implantation could provide a recovery effect in terms of improving cognitive performance – therefore this evidence intends to increase the public's awareness on the benefits of cochlear implants for those with severe-profound hearing loss but also more importantly among the clinicians.

In New Zealand, the public funding for cochlear implantation has been more difficult for adults than children who are eligible for full bilateral cochlear implantation while adults are only eligible for unilateral cochlear implantation through public funding. Furthermore, the limited funding results in a long waiting list for cochlear implantation in adults. This could also result in some ending up being on the waiting list for years due to having a lower priority than other candidates. In the 2021/22 budget, the government has injected 28 million dollars into the adult cochlear implant programme, resulting in 160 people are able to receive cochlear implantation through public funding, thus having the opportunity to access to sounds again (The Hearing House, May 20). Therefore, with increasing evidence from research on the effectiveness of cochlear implantation in restoring sound access to the brain, improving cognition, improving mental health and quality of life, this provides the path toward increasing public funding for cochlear implantation in adults in New Zealand.

5.7 Conclusion

In conclusion, the current study aimed to investigate the relationship between hearing loss and cognition in the older adult population with the addition of a hearing loss simulation group, so that the hearing loss factor itself can be isolated to investigate the potential causal relationship between the two. The main findings of this study were that the presence of hearing loss provides an immediate effect of poor performance in cognitive tasks when carried out auditorily due to excessive cognitive capacity needed for auditory processing, resulting in poor working memory. This therefore presents a "pseudo" cognitive impairment. This finding supports the overdiagnosis hypothesis and cognitive load hypothesis. Furthermore, as similar performances were found between the WL group (individuals with severe-profound hearing loss, unaided when tested), the CI group (cochlear implant users), and normally-hearing participants, this contributed evidence to the hypothesis of the protective effect of hearing assistive devices on cognitive decline. This also supports the cognitive load hypothesis where freed cognitive resources from amplification of auditory signals could result in improvement in cognitive performance. The findings of this study not only provide evidence for the effectiveness of hearing aid use and, more importantly, the impact of cochlear implantation for those with severe-profound hearing loss, and its support for more public funding for adult cochlear implantation in New Zealand.

Appendix A: Participant Information Sheet

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School of Population Health

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New Zealand

PARTICIPANT INFORMATION SHEET

Project Title: The impact of cochlear implantation on cognitive function in adults

Researcher: Connie Loi, Master of Audiology student, University of Auckland
Principle Investigator (Supervisor): Dr. David Welch, Department of Audiology, School of Population Health, University of Auckland

Project Description and Invitation

This research aims to investigate the association between hearing ability and cognitive function in adults. We will be assessing aspects of cognitive function including working memory, attention, encoding, auditory processing, verbal comprehension, and mental manipulation. We will obtain this information by inviting you to complete some cognitive tasks that are similar to puzzle-like tasks, and using your existing hearing data from your clinical records (if applicable).

We aim to compare the outcomes of these measures between four groups of participants: adults who currently have cochlear implants, adults awaiting cochlear implantation, adults who have normal hearing, and adults who have normal hearing with simulated hearing loss.

We would like to invite you to participate in this study if you are currently using a cochlear implant (for 6 months or more), are currently on the waiting list for cochlear implantation, or if you are an adult whose hearing is normal.

For participants with normal hearing, we will administer a short hearing screening (up to 15 minutes) at the start of session. For the testing, we will randomly assign you into either the control group or hearing loss simulation group. Hearing loss simulation will be carried out through recordings of the student researcher's speech, where the recordings will be presented electronically through a filter created by a computer. The filter creates a distortion (e.g reduced frequency resolution) and reduces the sound level of the recordings to a degree that is similar to a severe hearing loss. The distorted recordings will then be presented to the participants through insert earphones that are widely used in audiology clinics.

For cochlear implant users and those who are currently on the cochlear implantation waiting list, we will also obtain existing hearing data from clinical records at the Hearing House for research purposes. During the session, we will ask a few questions including:

- Date of birth and or age
- Duration of hearing loss since onset (if applicable)
- Implantation date and duration (if applicable)

Location, Duration, Reimbursement:

Testing will take place at **Building 507** of **The University of Auckland Grafton Campus**, located at **22-30 Park Ave, Grafton**. Testing will take up to 2 hours of your time (including rest breaks) in a one-off session. You will be reimbursed with a $10 petrol or supermarket voucher for your participation in the research, regardless of whether or not you complete all parts of testing.

Data Collection, Retention, and Privacy

With your consent, data will be stored confidentially in digital form on a password-protected computer and will be retained indefinitely for research purposes. Results from this research information which may reveal your identity will not be presented at any time. The summarised findings will be published in a Master's thesis and may be potentially used in scientific literature and/or presentations.

Right to Withdraw from Participation

Participation in this study is entirely voluntary. If for any reason you choose not to continue participating, at any point, you have the right to withdraw yourself and any information you have provided during the session, up until one month after recruitment.

Outcomes of Study

All participants will have the opportunity to view the results from this study. As with all publications of the work, this will be a summary of findings and no individuals will be identified. If you would like to receive this summary report after completion of the study, please indicate by circling 'Yes' on the consent form.

For normal hearing participants, if a hearing loss is found during hearing screening, we will recommend you seeing an audiologist for a full diagnostic hearing assessment and/or other specialist who may be able to assess and help with your hearing loss.

Contact details:

If you have any concerns or questions regarding this study, please contact the following:

Connie Loi, Co-investigator, Master of Audiology student, University of Auckland
E-mail: cloi408@aucklanduni.ac.nz

David Welch, Principal investigator (supervisor), Department of Audiology, School of Population Health, University of Auckland.
E-mail: d.welch@auckland.ac.nz
Contact phone: (09) 923 8404

Prof. Robert Scragg, Head of School, School of Population Health, University of Auckland.
E-mail: r.scragg@auckland.ac.nz
Contact phone: (09) 923 6336

If you have any questions or concerns regarding ethical concerns, you may contact the following:

The Chair, The Auckland Health Research Ethics Committee (AHREC), The University of Auckland, Research Office, Private Bag 92019, Auckland 1142.
E-mail: ahrec@auckland.ac.nz
Contact phone: (09) 373 7599 x 83711

Approved by the Auckland Health Research Ethics Committee on 14/10/2021 for three years. Reference number AH22816.

Appendix B: Consent Form

Department of Audiology
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School of Population Health

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New Zealand

CONSENT FORM

THIS FORM WILL BE HELD FOR 6 YEARS

Project Title
The impact of cochlear implantation on cognitive function in adults

Researcher
Connie Loi, Master of Audiology, University of Auckland

Supervisor
Dr. David Welch (Head of Audiology, Department of Audiology)

I agree to be a participant in this research. I have understood what this research is about and why I have been invited to participate. I have been given the opportunity to ask any questions I may have about this research and my role as a participant. The questions I have asked have been satisfactorily answered.

- I am freely choosing to participate in this research.
- I have been given a copy of the Participant Information Sheet for this research and have read and understood this in full.

I understand:

- I have a right to withdraw my participation from this research, including withdrawing my data, at any time during the research session, without providing a reason.
- My participation will take up to 2 hours in a one-off session, which will include rest breaks.
- During the testing session, I will be asked to do some cognitive tasks, which assess aspects of cognition such as working memory, attention, encoding, auditory processing, and mental manipulation. I will also be asked a few questions including:
    - Date of birth and/or age
    - Duration of hearing loss since onset (if applicable)
    - Implantation date and duration (if applicable)
- If I am participating as an individual with normal hearing, I will also be asked to complete a short hearing screening (up to 15 minutes) in addition to cognitive testing and interviewing.
- My data will be kept confidential and that there will be no information identifying my data as my own, or me as a participant in this study. My confidential data will be kept secure, in digital format, at The University of Auckland on a secure computer. This data will be kept indefinitely for future research. This consent form will be kept for a minimum of six years at The University of Auckland, after which it will be securely destroyed through a paper shredder.
- I will receive one $10 petrol or supermarket voucher for my participation, regardless of whether or not I complete all parts of the research.

☐ If I am a cochlear implant user, or on the waiting list for implantation, I give consent for my existing hearing data from my clinical records to be accessed and used by the researchers.

☐ For normal hearing participants, if a hearing loss is found during the hearing screening, I give consent for my existing hearing results to be accessed by other audiologists and specialists who may be able to assess and help with my hearing difficulties.

Name: ____

Signature: _________________________ **Date:** ________________

If you wish to receive a summary of the findings, please provide your contact email address below:

E-mail: ____

Approved by the Auckland Health Research Ethics Committee on 14/10/2021 for three years. Reference number AH22816.

Appendix C: Invitation Letter (CI group)

Hello,

I am sending this invitation on behalf of Connie Loi, who is completing her Master of Audiology degree. Her thesis research is investigating the effect of cochlear implantation on cognition in adults. You are an experienced cochlear implant user, therefore would be an ideal person to take part in this research.

An information sheet is attached, with more detail about this study and your involvement, but essentially you go to the University of Auckland and carry out some puzzle-like cognitive tasks. It takes around 1 hour and can be arranged at a time convenient for you. Through this research we believe that it will contribute concrete evidence in knowing the impact and benefits of cochlear implants for people with severe to profound hearing loss, especially in the adult population.

You will receive a $10 petrol or supermarket voucher to reimburse your travel costs.

If you may be interested to participate, please email Connie (details below). She is more than happy to answer your questions and will organise a suitable time and date for you.

Connie Loi (Master of Audiology)
Email: cloi408@aucklanduni.ac.nz

Again, a huge thank you in advance if you're joining this study!

Approved by the Auckland Health Research Ethics Committee on 14/10/2021 for three years. Reference number AH22816.

Appendix D: Invitation Letter (WL group)

Hello,

I am sending this invitation on behalf of Connie Loi, who is completing her Master of Audiology degree. Her thesis research is investigating the effect of cochlear implantation on cognition in adults. You are currently on the waiting list for cochlear implantation, therefore would be an ideal person to take part in this research.

An information sheet is attached, with more detail about this study and your involvement, but essentially you go to the University of Auckland and carry out some puzzle-like cognitive tasks. It takes around 1 hour and can be arranged at a time convenient for you. Through this research we believe that it will contribute concrete evidence in knowing the impact and benefits of cochlear implants for people with severe to profound hearing loss, especially in the adult population.

You will receive a $10 petrol or supermarket voucher to reimburse your travel costs.

If you may be interested to participate, please email Connie (details below). She is more than happy to answer your questions and will organise a suitable time and date for you.

Connie Loi (Master of Audiology)
Email: cloi408@aucklanduni.ac.nz

Again, a huge thank you in advance if you're joining this study!

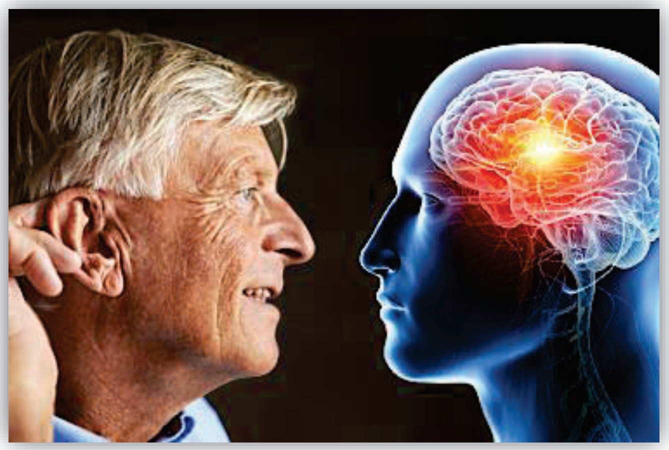
Approved by the Auckland Health Research Ethics Committee on 14/10/2021 for three years. Reference number AH22816.

Appendix E: Recruitment Poster (NH group)

THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

MEDICAL AND HEALTH SCIENCES
SCHOOL OF POPULATION HEALTH

Research Participants Needed



Are you aged 40 years old or above, and have normal hearing?

About this study

This study is looking into the relationship between hearing loss and cognitive function in adults. We are currently recruiting those who are 40 years old or older, with normal hearing.

Participants will complete:

- a 15-minute hearing screening to check for normal hearing
- some puzzle-like tasks

This study will take place at **University of Auckland Grafton Campus**. Testing will take up to 2 hours (including rest breaks) in a one-off session. Participants will receive $10 petrol or supermarket voucher for their participation.

IF YOU ARE INTERESTED IN PARTICIPATING, PLEASE CONTACT:

Name: Connie Loi (Master of Audiology, University of Auckland)

Email: cloi408@aucklanduni.ac.nz

Approved by the Auckland Health Research Ethics Committee on 14/10/2021 for three years. Reference number AH22816.

Appendix F: Interview Schedule (CI and WL groups)

Participant code: ________________

Please answer the following questions as applicable.

Date of birth: _____________ Age: __________

How long have you had your hearing loss for?

____

How long have you had your cochlear implants for? (Please include the implantation date if possible)

____

How long have you been on the waiting list for, to date? (If applicable)

____

Appendix G: Participant Information Sheet for The Hearing House

Department of Audiology
Faculty of Medical and Health Sciences
School of Population Health

Level 2, Building 507, School of Population Health
Faculty of Medical and Health Sciences
Grafton Campus
22-30 Park Ave
Grafton
audiology@auckland.ac.nz

The University of Auckland
Private Bag 92019
Auckland 1142
New Zealand

PARTICIPANT INFORMATION SHEET

Project Title: The impact of cochlear implantation on cognitive function in adults

Researcher: Connie Loi, Master of Audiology, University of Auckland
Supervisor: Dr David Welch, Department of Audiology, School of Population Health, University of Auckland

Project Description and Invitation

This research aims to investigate the association between hearing ability and cognitive function in adults. We will be assessing aspects of cognitive function including working memory, attention, auditory processing, verbal comprehension, and mental manipulation.

We aim to compare the outcomes of these measures between four participant groups: adults who currently have cochlear implants, adults awaiting cochlear implantation, adults with normal hearing, and adults with normal hearing for whom we will present stimuli that have been altered to simulate a hearing loss. Through this research, we are hoping that it will provide more insight about the impact of cochlear implantation on cognition in adults as well as the influence that cochlear implantation in this population. We believe that this will help to inform clinical treatment and the funding of cochlear implants in New Zealand in the future.

We would like the Hearing House to help us invite adults who currently have cochlear implants (for 6 months or more) and those who are currently on the waiting list for cochlear implantation to take part.

Data collection, Retention, and Privacy

With participants' consent, we would like to access data held by the Hearing House about their hearing ability to use in the research. These data will be de-identified and stored securely in digital form on a password-protected computer and will be retained indefinitely for research purposes. Results that could reveal a person's identity will not be presented at any time. The summarized findings will be published in a Master's thesis and may be potentially used in scientific literature and/or presentations.

Right to Withdraw from Participation

The Hearing House's cooperation in this study is entirely voluntary. If for any reason you choose not to continue participating, you can withdraw.

Outcomes of Study

If you would like to receive a summary report after completion of the study, please indicate on the consent form.

Contact details:

If you have any concerns or questions regarding this study, please contact the following:

Connie Loi, Co-investigator, Master of Audiology, University of Auckland
E-mail: cloi408@aucklanduni.ac.nz

David Welch, Principal Investigator, Department of Audiology, School of Population Health, University of Auckland.
E-mail: d.welch@auckland.ac.nz
Contact phone: (09) 923 8404

If you have any questions or concerns regarding ethical concerns, you may contact the following:

The Chair, The Auckland Health Research Ethics Committee (AHREC), The University of Auckland, Research Office, Private Bag 92019, Auckland 1142.
E-mail: ahrec@auckland.ac.nz
Contact phone: (09) 373 7599 x 83711

Approved by the Auckland Health Research Ethics Committee on 14/10/2021 for three years. Reference number AH22816.

Appendix H: Consent Form for The Hearing House

Department of Audiology
Faculty of Medical and Health Sciences
School of Population Health

Level 2, Building 507, School of Population Health
Faculty of Medical and Health Sciences
Grafton Campus
22-30 Park Ave
Grafton
audiology@auckland.ac.nz

The University of Auckland
Private Bag 92019
Auckland 1142
New Zealand

Consent form for CEO of the Hearing House

Research title: The impact of cochlear implantation on cognitive function in adults

Researcher: Connie Loi, Master of Audiology, University of Auckland

Supervisor: David Welch, Head of Audiology, Department of Audiology, University of Auckland

I have been given information about the research project.

I have read the participant information sheet and have had an opportunity to ask Connie Loi questions about the research and the cooperation of the Hearing House.

I understand that if I consent, the Hearing House will be asked to help in recruiting current cochlear implant users and those who are currently on the cochlear implantation waiting list.

I understand that by consenting, the Hearing House will allow consenting participants' existing hearing data from the clinical records to be accessed and used by the researchers.

I understand that I can contact the researchers at any time if I have concerns or complaints.

I understand that the consent to help in the research can be withdrawn at any time.

☐ I would like the Hearing House to receive a brief report of the summarized findings at the end of the project.

By signing below, I am indicating my consent for the Hearing House to cooperate in the research as described above.

Name: ____

Signature: _________________________ **Date:** ________________

Approved by the Auckland Health Research Ethics Committee on 14/10/2021 for three years. Reference number AH22816

REFERENCES

Allen, N. H., Burns, A., Newton, V., Hickson, F., Ramsden, R., Rogers, J., ... & Morris, J. (2003). The effects of improving hearing in dementia. *Age and Ageing*, *32*(2), 189-193.

Ariöz, U., & Günel, B. (2016). Evaluation of hearing loss simulation using a speech intelligibility index. *Turkish Journal of Electrical Engineering & Computer Sciences*, *24*(5), 4193-4207.

Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In *Psychology of Learning and Motivation* (Vol. 2, pp. 89-195). Academic Press.

Baddeley, A. (2000). The episodic buffer: a new component of working memory?. *Trends in Cognitive Sciences*, *4*(11), 417-423.

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

Baer, T., & Moore, B. C. (1993). Effects of spectral smearing on the intelligibility of sentences in noise. *The Journal of the Acoustical Society of America*, *94*(3), 1229-1241.

Baer, T., & Moore, B. C. (1994). Effects of spectral smearing on the intelligibility of sentences in the presence of interfering speech. *The Journal of the Acoustical Society of America*, *95*(4), 2277-2280.

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

Banich, M. T. (2009). Executive function: The search for an integrated account. *Current Directions in Psychological Science*, *18*(2), 89-94.

Barnes, D. E., & Yaffe, K. (2011). The projected effect of risk factor reduction on Alzheimer's disease prevalence. *The Lancet. Neurology*, *10*(9), 819–828. https://doi.org/10.1016/S1474-4422(11)70072-2

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child development*, *81*(6), 1641-1660.

Bilger, R. C., & Wang, M. D. (1976). Consonant confusions in patients with sensorineural hearing loss. *Journal of Speech and Hearing Research*, *19*(4), 718-748.

Blamey, P. J., Cowan, R. S. C., DipAud, J. I. A., & DipAud, L. A. (1989). Speech perception using combinations of auditory, visual, and. *Journal of Rehabilitation Research and Development*, *26*(1-4), 15.

Bulgarelli, D., & Molina, P. (2016). Social cognition in preschoolers: Effects of early experience and individual differences. *Frontiers in Psychology*, *7*, 1762.

Cacioppo, J. T., & Hawkley, L. C. (2009). Perceived social isolation and cognition. *Trends in Cognitive Sciences*, *13*(10), 447-454.

Carhart, R. (1945). An improved method for classifying audiograms. *The Laryngoscope*, *55*(11), 640-662.

Chai, W. J., Abd Hamid, A. I., & Abdullah, J. M. (2018). Working memory from the psychological and neurosciences perspectives: a review. *Frontiers in psychology*, *9*, 401.

Chisolm, T. H., Johnson, C. E., Danhauer, J. L., Portz, L. J., Abrams, H. B., Lesner, S., ... & Newman, C. W. (2007). A systematic review of health-related quality of life and hearing aids: final report of the American Academy of Audiology Task Force on the Health-Related Quality of Life Benefits of Amplification in Adults. *Journal of the American Academy of Audiology*, *18*(02), 151-183.

Choi, A. Y., Shim, H. J., Lee, S. H., Yoon, S. W., & Joo, E. J. (2011). Is cognitive function in adults with hearing impairment improved by the use of hearing aids?. *Clinical and Experimental Otorhinolaryngology*, *4*(2), 72.

Ciorba, A., Bianchini, C., Pelucchi, S., & Pastore, A. (2012). The impact of hearing loss on the quality of life of elderly adults. *Clinical Interventions in Aging*, *7*, 159.

Clark, J. G. (1981). Uses and abuses of hearing loss classification. *ASHA*, *23*(7), 493-500.

Coulacoglou, C., & Saklofske, D. H. (2017). Executive function, theory of mind, and adaptive behavior. *Psychomterics and Psychological assessment. Principles and applications*, 91-119.

Dalebout, S. (2008). *The Praeger Guide to Hearing and Hearing Loss: Assessment, Treatment, and Prevention: Assessment, Treatment, and Prevention*. ABC-CLIO.

Dawes, P., Cruickshanks, K. J., Fischer, M. E., Klein, B. E., Klein, R., & Nondahl, D. M. (2015). Hearing-aid use and long-term health outcomes: Hearing handicap, mental health, social engagement, cognitive function, physical health, and mortality. *International Journal of Audiology*, *54*(11), 838-844.

Dell'Aringa, A. H. B., Adachi, E. S., & Dell'Aringa, A. R. (2007). Lip reading role in the hearing aid fitting process. *Revista Brasileira de Otorrinolaringologia*, *73*, 101-105.

Demorest, M. E., & Bernstein, L. E. (1992). Sources of variability in speechreading sentences: A generalizability analysis. *Journal of Speech, Language, and Hearing Research*, *35*(4), 876-891.

Desjardins, J. L. (2016). Analysis of performance on cognitive test measures before, during, and after 6 months of hearing aid use: A single-subject experimental design. *American Journal of Audiology*, *25*(2), 127-141.

Desloge, J. G., Reed, C. M., Braida, L. D., Perez, Z. D., & Delhorne, L. A. (2010). Speech reception by listeners with real and simulated hearing impairment: Effects of continuous and interrupted noise. *The Journal of the Acoustical Society of America*, *128*(1), 342-359.

Desloge, J. G., Reed, C. M., Braida, L. D., Perez, Z. D., & Delhorne, L. A. (2011a). Temporal modulation transfer functions for listeners with real and simulated hearing loss. *The Journal of the Acoustical Society of America*, *129*(6), 3884-3896.

Desloge, J. G., Reed, C. M., Braida, L. D., Perez, Z. D., & Delhorne, L. A. (2011b). Temporal masking functions for listeners with real and simulated hearing loss. *The Journal of the Acoustical Society of America*, *130*(2), 915-932.

Desloge, J. G., Reed, C. M., Braida, L. D., Perez, Z. D., & Delhorne, L. A. (2012). Auditory-filter characteristics for listeners with real and simulated hearing impairment. *Trends in Amplification*, *16*(1), 19-39.

Diego, Z., & Maurizio, G. (2006). Current Outcomes and Future Perspectives of Cochlear Implants. *Current Drug Therapy*, *1*(2), 231-239.

Doherty, K. A., & Desjardins, J. L. (2015). The benefit of amplification on auditory working memory function in middle-aged and young-older hearing impaired adults. *Frontiers in Psychology*, *6*, 721.

Duchnowski, P., & Zurek, P. M. (1995). Villchur revisited: Another look at automatic gain control simulation of recruiting hearing loss. *The Journal of the Acoustical Society of America*, *98*(6), 3170-3181.

Dupuis, K., Pichora-Fuller, M. K., Chasteen, A. L., Marchuk, V., Singh, G., & Smith, S. L. (2015). Effects of hearing and vision impairments on the Montreal Cognitive Assessment. *Aging, Neuropsychology, and Cognition*, *22*(4), 413-437.

Edition, F. (2013). Diagnostic and statistical manual of mental disorders. *Am Psychiatric Assoc*, *21*, 591-643.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science*, *11*(1), 19-23.

Epstein, M., & Marozeau, J. (2010). Loudness and intensity coding, in C. J. Plack (Eds.), *The Oxford Handbook of Auditory Science: Hearing (Vol. 3)* (pp. 45-71). Oxford University Press.

Eysenck, M. W. (1978). Levels of processing: A critique. *British Journal of Psychology*, *69*(2), 157-169.

Fallon, J. B., Irvine, D. R., & Shepherd, R. K. (2008). Cochlear implants and brain plasticity. *Hearing Research*, *238*(1-2), 110-117.

Fiske, S. T., & Taylor, S. E. (2013). *Social cognition: From brains to culture*. Sage.

Füllgrabe, C. (2020). On the possible overestimation of cognitive decline: the impact of age-related hearing loss on cognitive-test performance. *Frontiers in Neuroscience*, *14*, 454.

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

Gates, G. A., Anderson, M. L., Feeney, M. P., McCurry, S. M., & Larson, E. B. (2008). Central auditory dysfunction in older persons with memory impairment or Alzheimer dementia. *Archives of Otolaryngology–Head & Neck Surgery*, *134*(7), 771-777.

Gates, G. A., Anderson, M. L., McCurry, S. M., Feeney, M. P., & Larson, E. B. (2011). Central auditory dysfunction as a harbinger of Alzheimer dementia. *Archives of Otolaryngology–Head & Neck Surgery*, *137*(4), 390-395.

Gates, G. A., Cobb, J. L., Linn, R. T., Rees, T., Wolf, P. A., & D'Agostino, R. B. (1996). Central auditory dysfunction, cognitive dysfunction, and dementia in older people. *Archives of Otolaryngology–Head & Neck Surgery*, *122*(2), 161-167.

Gilbert, S. J., & Burgess, P. W. (2008). Executive function. *Current Biology*, *18*(3), R110-R114.

Golub, J. S. (2017). Brain changes associated with age-related hearing loss. *Current Opinion in Otolaryngology & Head and Neck Surgery*, *25*(5), 347-352.

Goodman, A. (1965). Reference zero levels for pure-tone audiometer. *ASHA*, *7*(262), 1.

Grason-Stadler. (n.d.). *GSi Audiostar Pro user manual.* https://www.manualslib.com/manual/1288869/Gsi-Audiostar-Pro.html

Hsiao, Y. H., Chang, C. H., & Gean, P. W. (2018). Impact of social relationships on Alzheimer's memory impairment: mechanistic studies. *Journal of Biomedical Science*, *25*(1), 1-8.

Humes, L. E., Dirks, D. D., Bell, T. S., & Kincaid, G. E. (1987). Recognition of nonsense syllables by hearing‐impaired listeners and by noise‐masked normal hearers. *The Journal of the Acoustical Society of America*, *81*(3), 765-773.

Jafari, Z., Kolb, B. E., & Mohajerani, M. H. (2019). Age-related hearing loss and tinnitus, dementia risk, and auditory amplification outcomes. *Ageing Research Reviews*, *56*, 100963.

Jorgensen, L., Palmer, C., & Fischer, G. (2014). Evaluation of hearing status at the time of dementia diagnosis. *Audiology Today*, *26*(1), 38-32.

Jorgensen, L. E., Palmer, C. V., Pratt, S., Erickson, K. I., & Moncrieff, D. (2016). The effect of decreased audibility on MMSE performance: a measure commonly used for diagnosing dementia. *Journal of the American Academy of Audiology*, *27*(04), 311-323.

Katz, J., Chasin, M., English, K. M., Hood, L. J., & Tillery, K. L. (Eds.). (2015). *Handbook of clinical audiology* (Vol. 7). Philadelphia, PA: Wolters Kluwer Health.

Kemtes, K. A., & Allen, D. N. (2008). Presentation modality influences WAIS Digit Span performance in younger and older adults. *Journal of Clinical and Experimental Neuropsychology*, *30*(6), 661-665.

Kumar, P., & Yathiraj, A. (2009). Perception of speech simulating different configurations of hearing loss in normal hearing individuals. *Clinical Linguistics & Phonetics*, *23*(9), 680-687.

Lawrence, B. J., Jayakody, D. M., Henshaw, H., Ferguson, M. A., Eikelboom, R. H., Loftus, A. M., & Friedland, P. L. (2018). Auditory and cognitive training for cognition in adults with hearing loss: A systematic review and meta-analysis. *Trends in hearing*, *22*, 2331216518792096.

Lin, F. R., & Albert, M. (2014). Hearing loss and dementia–who is listening?. *Aging & Mental Health*, *18*(6), 671-673.

Lin, F. R., Ferrucci, L., Metter, E. J., An, Y., Zonderman, A. B., & Resnick, S. M. (2011a). Hearing loss and cognition in the Baltimore Longitudinal Study of Aging. *Neuropsychology*, *25*(6), 763.

Lin, F. R., Metter, E. J., O'Brien, R. J., Resnick, S. M., Zonderman, A. B., & Ferrucci, L. (2011b). Hearing loss and incident dementia. *Archives of Neurology*, *68*(2), 214-220.

Lin, F. R., Yaffe, K., Xia, J., Xue, Q. L., Harris, T. B., Purchase-Helzner, E., ... & Health ABC Study Group, F. T. (2013). Hearing loss and cognitive decline in older adults. *JAMA Internal Medicine*, *173*(4), 293-299.

Lin, M. Y., Gutierrez, P. R., Stone, K. L., Yaffe, K., Ensrud, K. E., Fink, H. A., ... & Mangione, C. M. (2004). Vision impairment and combined vision and hearing impairment predict cognitive and functional decline in older women. *Journal of the American Geriatrics Society*, *52*(12), 1996-2002.

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

Livingston, G., Huntley, J., Sommerlad, A., Ames, D., Ballard, C., Banerjee, S., ... & Mukadam, N. (2020). Dementia prevention, intervention, and care: 2020 report of the Lancet Commission. *The Lancet*, *396*(10248), 413-446.

Lloyd, L. L., & Kaplan, H. (1978). *Audiometric interpretation: A manual of basic audiometry* (Vol. 1). University Park Press.

Loughrey, D. G., Kelly, M. E., Kelley, G. A., Brennan, S., & Lawlor, B. A. (2018). Association of age-related hearing loss with cognitive function, cognitive impairment, and dementia: a systematic review and meta-analysis. *JAMA otolaryngology–head & neck surgery*, *144*(2), 115-126.

Lum, D. S., & Braida, L. D. (2000). Perception of speech and non-speech sounds by listeners with real and simulated sensorineural hearing loss. *Journal of Phonetics*, *28*(3), 343-366.

Maturana, H. R. (1978). Cognition. In *Wahrnehmung und Kommunikation* (pp. 29-49). Peter Lang.

Mick, P., Kawachi, I., & Lin, F. R. (2014). The association between hearing loss and social isolation in older adults. *Otolaryngology–Head and Neck Surgery*, *150*(3), 378-384.

Ministry of Health. (2021, May 19). *Cochlear implants.* https://www.health.govt.nz/your-health/services-and-support/disability-services/types-disability-support/hearing-and-vision-services/hearing-services/cochlear-implants

Møller, A. R. (2006). History of cochlear implants and auditory brainstem implants. *Cochlear and brainstem implants*, *64*, 1-10.

Moore, B. C. (2007). *Cochlear hearing loss: physiological, psychological and technical issues*. John Wiley & Sons.

Moore, B. C. J., & Glasberg, B. R. (1997). A model of loudness perception applied to cochlear hearing loss. *Auditory Neuroscience*, *3*(3), 289-311.

Moore, B. C., & Glasberg, B. R. (1993). Simulation of the effects of loudness recruitment and threshold elevation on the intelligibility of speech in quiet and in a background of speech. *The Journal of the Acoustical Society of America*, *94*(4), 2050-2062.

Mosnier, I., Bebear, J. P., Marx, M., Fraysse, B., Truy, E., Lina-Granade, G., ... & Sterkers, O. (2015). Improvement of cognitive function after cochlear implantation in elderly patients. *JAMA Otolaryngology–Head & Neck Surgery*, *141*(5), 442-450.

Mulrow, C. D., Tuley, M. R., & Aguilar, C. (1992). Correlates of successful hearing aid use in older adults. *Ear and Hearing*, *13*(2), 108-113.

Munro, M. J. (1995). Nonsegmental factors in foreign accent: Ratings of filtered speech. *Studies in Second Language Acquisition*, *17*(1), 17-34.

Musiek, F. E., & Baran, J. A. (2018). *The auditory system: Anatomy, physiology, and clinical correlates*. Plural Publishing.

Nazzi, T., Bertoncini, J., & Mehler, J. (1998). Language discrimination by newborns: toward an understanding of the role of rhythm. *Journal of Experimental Psychology: Human perception and performance*, *24*(3), 756.

Nejime, Y., & Moore, B. C. (1997). Simulation of the effect of threshold elevation and loudness recruitment combined with reduced frequency selectivity on the intelligibility of speech in noise. *The Journal of the Acoustical Society of America*, *102*(1), 603-615.

Nittrouer, S., Tarr, E., Wucinich, T., Moberly, A. C., & Lowenstein, J. H. (2015). Measuring the effects of spectral smearing and enhancement on speech recognition in noise for adults and children. *The Journal of the Acoustical Society of America*, *137*(4), 2004-2014.

Olson, E., & Luciana, M. M. (2008). The development of prefrontal cortex functions in adolescence: Theoretical models and a possible dissociation of dorsal versus ventral subregions. In *The Handbook of Developmental Cognitive Neuroscience*. MIT Press.

Oxenham, A. J., & Bacon, S. P. (2003). Cochlear compression: perceptual measures and implications for normal and impaired hearing. *Ear and Hearing*, *24*(5), 352-366.

Park, S. Y., Kim, M. J., Kim, H. L., Kim, D. K., Yeo, S. W., & Park, S. N. (2018). Cognitive decline and increased hippocampal p-tau expression in mice with hearing loss. *Behavioural Brain Research*, *342*, 19-26.

Peters, C. A., Potter, J. F., & Scholer, S. G. (1988). Hearing impairment as a predictor of cognitive decline in dementia. *Journal of the American Geriatrics Society*, *36*(11), 981-986.

Phillips, L. H., Wynn, V. E., McPherson, S., & Gilhooly, K. J. (2001). Mental planning and the Tower of London task. *The Quarterly Journal of Experimental Psychology Section A*, *54*(2), 579-597.

Prince, M., Comas-Herrera, A., Knapp, M., Guerchet, M., & Karagiannidou, M. (2016). World Alzheimer report 2016: Improving healthcare for people living with dementia: coverage, quality and costs now and in the future. *Alzheiner's Disease International (ADI), London, UK.* [*https://www.alzint.org/*](https://www.alzint.org/)

Rabbitt, P. (1991). Mild hearing loss can cause apparent memory failures which increase with age and reduce with IQ. *Acta Oto-laryngologica*, *111*(sup476), 167-176.

Rigters, S. C., Bos, D., Metselaar, M., Roshchupkin, G. V., Baatenburg de Jong, R. J., Ikram, M. A., ... & Goedegebure, A. (2017). Hearing impairment is associated with smaller brain volume in aging. *Frontiers in Aging Neuroscience*, *9*, 2.

Sachdev, P. S., Blacker, D., Blazer, D. G., Ganguli, M., Jeste, D. V., Paulsen, J. S., & Petersen, R. C. (2014). Classifying neurocognitive disorders: the DSM-5 approach. *Nature Reviews Neurology*, *10*(11), 634.

Schlauch RS & Nelson P (2015). Puretone evaluation, in J. Katz, M. Chasin, K. English, L. J. Hood, & K. L. Tillery (Eds.), *Handbook of Clinical Audiology* (pp. 29-48). Wolters Kluwer Health.

Shimamura, A. P. (2000). The role of the prefrontal cortex in dynamic filtering. *Psychobiology*, *28*(2), 207-218.

Smith, S. L., & Pichora-Fuller, M. K. (2015). Associations between speech understanding and auditory and visual tests of verbal working memory: effects of linguistic complexity, task, age, and hearing loss. *Frontiers in Psychology*, 1394.

Snowdon, D. A., Greiner, L. H., Mortimer, J. A., Riley, K. P., Greiner, P. A., & Markesbery, W. R. (1997). Brain infarction and the clinical expression of Alzheimer disease: the Nun Study. *JAMA*, *277*(10), 813-817.

Stevenson, J., McCann, D., Watkin, P., Worsfold, S., Kennedy, C., & Hearing Outcomes Study Team. (2010). The relationship between language development and behaviour problems in children with hearing loss. *Journal of Child Psychology and Psychiatry*, *51*(1), 77-83.

Sugawara, N., Sasaki, A., Yasui-Furukori, N., Kakehata, S., Umeda, T., Namba, A., ... & Kaneko, S. (2011). Hearing impairment and cognitive function among a community-dwelling population in Japan. *Annals of General Psychiatry*, *10*(1), 1-6.

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and instruction*, *4*(4), 295-312.

Swords, G. M., Nguyen, L. T., Mudar, R. A., & Llano, D. A. (2018). Auditory system dysfunction in Alzheimer disease and its prodromal states: A review. *Ageing Research Reviews*, *44*, 49-59.

Ter Keurs, M., Festen, J. M., & Plomp, R. (1992). Effect of spectral envelope smearing on speech reception. I. *The Journal of the Acoustical Society of America*, *91*(5), 2872-2880.

Ter Keurs, M., Festen, J. M., & Plomp, R. (1993). Effect of spectral envelope smearing on speech reception. II. *The Journal of the Acoustical Society of America*, *93*(3), 1547-1552.

Tesch-Römer, C. (1997). Psychological effects of hearing aid use in older adults. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *52*(3), P127-P138.

The Hearing House. (2021, May 20.) *Budget 2021: More adults to gain access to sound through cochlear implant technology*. https://www.hearinghouse.co.nz/single-post/budget-2021-more-adults-to-gain-access-to-sound-through-cochlear-implant-technology

The Hearing House. (n.d.). *Health professionals*. https://www.hearinghouse.co.nz/health-professionals

Tran, Y., Tang, D., Lo, C., McMahon, C., Mitchell, P., & Gopinath, B. (2021). Co-occurring hearing loss and cognitive decline in older adults: a dual group-based trajectory modeling approach. *Frontiers in Aging Neuroscience*, *13*.

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

van Hooren, S. A., Anteunis, L. J., Valentijn, S. A., Bosma, H., Ponds, R. W. H. M., Jolles, J., & van Boxtel, M. P. J. (2005). Does cognitive function in older adults with hearing impairment improve by hearing aid use?. *International Journal of Audiology*, *44*(5), 265-271.

Villchur, E. (1973). Signal processing to improve speech intelligibility in perceptive deafness. *The Journal of the Acoustical Society of America*, *53*(6), 1646-1657.

Villchur, E. (1974). Simulation of the effect of recruitment on loudness relationships in speech. *The Journal of the Acoustical Society of America*, *56*(5), 1601-1611.

Völter, C., Götze, L., Dazert, S., Falkenstein, M., & Thomas, J. P. (2018). Can cochlear implantation improve neurocognition in the aging population?. *Clinical Interventions in Aging*, *13*, 701.

Vos, T., Abajobir, A. A., Abate, K. H., Abbafati, C., Abbas, K. M., Abd-Allah, F., ... & Criqui, M. H. (2017). Global, regional, and national incidence, prevalence, and years lived with disability for 328 diseases and injuries for 195 countries, 1990–2016: a systematic analysis for the Global Burden of Disease Study 2016. *The Lancet*, *390*(10100), 1211-1259.

Wang, M. D., Reed, C. M., & Bilger, R. C. (1978). A comparison of the effects of filtering and sensorineural hearing loss on patterns of consonant confusions. *Journal of Speech and Hearing Research*, *21*(1), 5-36.

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

Welch, D., & Dawes, P. J. (2007). Variation in the normal hearing threshold predicts childhood IQ, linguistic, and behavioral outcomes. *Pediatric Research*, *61*(6), 737-744.

Wechsler, D. (2008). Wechsler adult intelligence scale–Fourth Edition (WAIS–IV). *San Antonio, TX: NCS Pearson*, *22*(498), 816-827.

Wilson, R. S., Beckett, L. A., Barnes, L. L., Schneider, J. A., Bach, J., Evans, D. A., & Bennett, D. A. (2002). Individual differences in rates of change in cognitive abilities of older persons. *Psychology and Aging*, *17*(2), 179.

Wong, C. G., Rapport, L. J., Billings, B. A., Ramachandran, V., & Stach, B. A. (2019). Hearing loss and verbal memory assessment among older adults. *Neuropsychology*, *33*(1), 47.

World Health Organization (WHO). (2021). *World report on hearing*. https://www.who.int/publications/i/item/world-report-on-hearing

Xie, R. (2016). Transmission of auditory sensory information decreases in rate and temporal precision at the endbulb of Held synapse during age-related hearing loss. *Journal of Neurophysiology*, *116*(6), 2695-2705.

Xu, B. R., & Mok, P. (2012, May 26-29). *Intonation perception of low-pass filtered speech in Mandarin and Cantonese* [Paper presentation]. In Tonal Aspects of Languages-Third International Symposium.

Zeng, F. G., & Djalilian, H. (2010). Hearing impairment, in C. J. Plack (Eds.), *The Oxford Handbook of Auditory Science: Hearing (Vol. 3)* (pp. 325-347). Oxford University Press.

Zurek, P. M., & Delhorne, L. A. (1987). Consonant reception in noise by listeners with mild and moderate sensorineural hearing impairment. *The Journal of the Acoustical Society of America*, *82*(5), 1548-1559