IS AUDITORY-VISUAL INTEGRATION A FACTOR IN HEARING AID OUTCOMES?

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E. R. Andre

University of Canterbury

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ABSTRACT

Aims: The first aim of this study was to begin to understand the relationships between hearing aid outcomes and the ability to integrate visual information with auditory information. No published studies have researched these relationships. Understanding these relationships may help in determining hearing aid candidacy or assist in determining the most appropriate rehabilitation pathways, including the provision of perceptual training to improve the use of visual information.

The second aim of this study was to determine if the University of Canterbury Auditory-visual Matrix Sentence Test (UCAMST) could potentially replace the need for QuickSIN testing of Signal-to-Noise Ratio (SNR) performance loss.

The third aim of this study was to provide practical usage evaluation to the developers of the UCAMST.

Method: A group of 12 participants aged 65 to 86 years were tested for their ability to understand speech-in-noise in the auditory-alone, auditory-visual, and visual-alone conditions. Speech tests were administered using the UCAMST and QuickSIN test. Hearing aid outcomes were assessed using the International Outcomes Inventory for Hearing Aids (IOI-HA) questionnaire. The measured Auditory Visual Enhancement (AVE) for understanding speech-in-noise in the auditory-visual condition compared with the auditory-alone condition, was correlated with IOI-HA questionnaire responses. Measurements were also made for potential control covariates found in the literature.

Results: All correlations between AVE and hearing aid outcomes were greater than zero (r_s of 0.130 to 0.496) but did not meet the threshold of statistical significance ($p < 0.05$). Measurements for

predictor, outcome, and covariate variables showed substantial agreement with results published in literature.

UCAMST results had a significant correlation with QuickSIN test results.

Conclusion: Findings from this study were inconclusive due to low statistical power. Further study into the relationships between AVE and hearing aid outcomes using larger groups of participants seems warranted.

The UCAMST may be able to replace the need for QuickSIN testing, after confirmation from further studies using diverse demographic groups of participants.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND TERMS

APHAB
Abbreviated Profile of Hearing Aid Benefit questionnaire.

Auditory-alone
Recognising speech by listening to sound without being able to see the face and lips of the person talking.

Auditory-visual
Recognising speech by listening to sound while receiving visual speech information by being able to see the face and lips of the person talking.

AVE
Auditory-Visual Enhancement. A numeric score measure of AVI skill or ability. The present study expressed AVE as the difference between the percent correct listening to speech-in-noise at the same signal-to-noise-ratio for the auditory-visual and auditory-alone conditions. Raw AVE scores were normalised by the maximum possible enhancement from auditory-alone scores using the formula AVE = (AV – A) / (1 – A). Some studies in literature expressed AVE using dB changes in SNR for the same percentage of words correct.

AVI
Auditory-Visual Integration. A mental process where a person combines an auditory signal and a visual signal to determine what words were said by a person speaking.

CNS
Central Nervous System

Client
A person seeking services for assistance with possible hearing impairment.

Conductive hearing impairment
Attenuation of the amplitude of sound as it travel along the auditory pathway towards the inner ear.

Hearing disability
A consequence of hearing impairment. Examples of hearing disability are activity limitations such as difficulty understanding conversation and difficulty understanding televisions.

Hearing Handicap
A consequence of hearing impairment. Examples of hearing handicap are participation restrictions such as not attending social situations like family dinners or club functions.

IOI-HA
International Outcomes Inventory for Hearing Aids questionnaire.

IOI_HA-Average
Mean of IOI-HA outcome questions 1 to 7. This is the global score or outcome of the questionnaire.

IOI-HA-Q1: Hours of daily use (USE)
IOI-HA-Q2: Benefit (Ben)
IOI-HA-Q3: Residual activity limitations (RAL)
IOI-HA-Q4: Satisfaction (Sat)
IOI-HA-Q5: Residual participation restrictions (RPR)
IOI-HA-Q6: Impact on others (Ioth)
IOI-HA-Q7: Quality of life (QoL)

Lipreading
Lipreading is the understanding of speech in the visual-alone condition (without hearing any speech sound).

MST
Matrix Sentence Test. A test where sentences re-use the same word recordings so that all sentences have the same sound content. Each sentence has the same grammatical structure.

MMSE
Mini-Mental State Exam. A screening questionnaire for dementia.

MoCA
Montreal Cognitive Assessment. A screening questionnaire for mild cognitive impairment.

NAL-NL2
National Acoustics Laboratory – Non-Linear version 2. A hearing aid fitting prescription.

NZAS
New Zealand Audiological Society.

Participant
A person who volunteered to be included in a research study.

Presbycusis
Hearing impairment associated with ageing.

PTA
Pure Tone Average. The average pure tone hearing threshold on an audiogram at several important speech frequencies. The chosen frequencies vary depending upon which professional body defined the standard. In New Zealand, the PTA is the average of 1 kHz and 4 kHz thresholds using the Best Practice Guidelines published by NZAS (2007).

QuickSIN
Quick Speech-In-Noise test.

Recommended sound level
The sound level setting on the UCAMST recommended by a procedure designed in the present study that uses the Verifit1 instrument and the NAL-NL2 hearing aid fitting prescription.

RST
Reading Span Test. A measure of working memory.

SNHI
Sensorineural Hearing Impairment

SNR
Signal to Noise Ratio

SNR_20%
SNR that results in a participant achieving 20% of words correct in the auditory-alone condition.

SNR_80%
SNR that results in a participant achieving 80% of words correct in the auditory-alone condition.

Speechreading
Another term for AVI used in some literature.

SRT
Speech Reception Threshold. The SRT threshold SNR or sound intensity level is the condition under which a score of 50% correct is obtained.

SRTn
SRT in noise

UC
University of Canterbury

UCAMST
University of Canterbury Auditory-visual Matrix Sentence Test

UND
University of Notre Dame

UCSHC
University of Canterbury Speech and Hearing Clinic

Verifit1
Audioscan Verifit1 Real Ear Measurement clinical test instrument.

Visual-alone
Recognising speech by receiving visual speech information by being able to see the face and lips of the person talking while not being able to hear the speech sounds.

1 CHAPTER ONE: Introduction

1.1 Introduction to the problem

1.1.1 Hearing impairment

Hearing impairment is a common disability in New Zealand. A survey by Greville (2005) reported a prevalence of hearing impairment in New Zealand of 10.3% of the general population. Breaking down the population of people with hearing impairment by age showed that 8% were aged under 14 years and that 33% were aged 45 to 64 years. Approximately 23% of the population aged 65 years and older were found to have hearing impairment causing disability. The present study involves rehabilitation outcome prediction research for older adults with hearing impairment in New Zealand. The potential significance of such research is evidenced by the high degree of prevalence of hearing impairment in this population.

The prevalence of hearing impairment in New Zealand is similar to that found in other advanced countries. The prevalence reported in the general population depends to some extent upon the criteria used to define hearing impairment. An Australian study reported the prevalence of hearing impairment among the general population at 17.4% (Exeter et al., 2015). In the general population, approximately 11% had mild hearing impairment and 6% had moderate or severe hearing impairment. In the United States the prevalence of hearing impairment was estimated to be 30% to 40% in the population aged 65 to 74 years and 50% to 80% in the population aged 75 years and older (Cruickshanks et al., 1998; Lemke, 2011; U.S. Congress, 1986).

1.1.2 Impact of hearing impairment

Hearing impairment creates a range of consequences. These include difficulties with communicating in noisy environments or with fast or unfamiliar speakers (Lemke, 2011), social and emotional

isolation (Lemke, 2011), greater dysfunction for physical and mental health (Chia et al., 2007; Dalton et al., 2003), negative impact on perception of overall quality of life (Chia et al., 2007), and negative consequences at work (Jennings & Shaw, 2008).

Hearing impairment has been found to have a significant relationship with mental health (Morgan, Hickson, & Worrall, 2002). These relationships were found to be independent of age. Severe to profound hearing impairment was found to be positively related to depression and anxiety (Carlsson et al., 2015). In addition the tinnitus and vertigo associated with the severe to profound hearing impairment was found to have a negative effect on quality of life (Carlsson et al., 2015).

1.1.3 Causes of hearing impairment

Hearing impairment can result from disorders in any part of the auditory pathway (Katz et al., 2009). Disorders of the outer and middle ear produce conductive hearing impairment. A conductive hearing impairment involves the attenuation of the amplitude of sound as it travel along the auditory pathway towards the inner ear. Disorders of the inner ear, nerves, and brain stem produce sensorineural hearing impairment (SNHI). SNHI involves the reduced ability to detect, transmit, and process sound. Brain disorders involving the reduced ability to process language are not considered to be SNHI.

Conductive and sensorineural hearing impairment can be caused by a range of diseases and conditions (Katz et al., 2009) including genetics, infections, noise exposure, and age. Some of these causes are more common in children and some are more common in adults. The present study only considers older adults with hearing impairment meeting certain criteria. The most common causes compatible with these criteria are presbycusis and noise exposure.

Presbycusis is hearing impairment associated with ageing (Katz et al., 2009). It is typically observed after the age of 60 years. Presbycusis affects the inner ear and may also effect the auditory neural

pathway. Presbycusis typically results in a SNHI in frequencies above 1000 Hz with the impairment being greater at higher frequencies. This high frequency hearing impairment reduces both sensitivity to low intensity sound and the ability to detect the presence of multiple sounds in adjacent frequency regions (Dillon, 2012).

Noise induced hearing impairment has a similar symptom to presbycusis. It affects hearing in higher frequencies like presbycusis. Noise induced hearing impairment often creates the greatest hearing impairment at frequencies from 3000 Hz to 6000 Hz (Katz et al., 2009).

1.1.4 Diagnosis of hearing impairment

In New Zealand, as in other advanced countries, hearing impairment is usually diagnosed using audiometry in a private or hospital hearing clinic setting (Katz et al., 2009; New Zealand Audiological Society (NZAS), 2007). The clinician administers a battery of tests with the test results being captured on a document called an "audiogram". The test procedures usually followed in New Zealand are defined in the Best Practice Guidelines published by NZAS (2007). The results of a hearing assessment typically contain the following sections for the right and left ears individually: pure tone audiometry, speech audiometry, tympanometry, acoustic reflex thresholds, and otoacoustic emissions.

1.1.4.1 Pure tone audiometry

The pure tone audiogram is a graph of frequency on the X axis and hearing threshold on the Y axis. For adults, the pure tone audiogram is produced via behavioural testing using pure tone sounds of various frequency and intensity levels. The pure tone audiogram assesses a person's sensitivity to sounds of various frequencies. Sounds are delivered via both air and bone conduction. The air conduction results show the person's hearing using the entire auditory pathway. The bone conduction results show the underlying hearing ability of the inner ear, nerves, and brain after any potential sound

attenuation through the outer and middle ears has been essentially by-passed. A gap between the air conduction and bone conduction results suggests a disorder in the outer or middle ear that is attenuating sound levels. The completed pure tone audiogram shows the degree of any hearing impairment, its configuration with regards to frequency, and helps to identify the location of disorders between the parts of ear anatomy. The pure tone audiogram is banded along the Y axis with hearing impairment categories that range from normal hearing, through mild and moderate hearing impairment, and end in severe to profound hearing impairment.

1.1.4.2 Speech audiometry

Carhart (1951) defined speech audiometry as a technique wherein standardized samples of a language are presented through a calibrated system to measure some aspect of hearing ability. There is a wide variety of tests in this category of assessment (as described in Section 1.1.5 below), but in New Zealand speech audiometry is typically performed using recorded single words presented in a quiet background at various sound intensity levels (NZAS, 2007). The response format is “open-set” in that the person being tested listens to words presented and repeats them back to the clinician administering the test. The expected sound level that corresponds to 50% of word phonemes correct can be calculated from the pure tone audiogram. If the sound level that results in 50% correct is within the expected range of the calculated sound level, then the person's ability to understand speech is consistent with their pure tone audiogram. Consistency provides a cross check on the pure tone results and also suggests that any requirement for increased sound levels for the person to understand speech are a consequence of the impairment of hearing sensitivity at various frequencies. If the speech audiometry results are worse than the expected sound level range, then this suggests that some portion of the person's requirement for increased sound levels is a consequence of a disorder in the processing of sound in the brain.

The results from both pure tone audiometry and speech audiometry are the most relevant to the present study. They are used by clinicians for diagnostic purposes, and to make treatment option recommendations, often in combination with other information obtained from questionnaires. The present study considers alternative speech testing measures that may be able to improve the quality of treatment option recommendations.

1.1.4.3 Other hearing tests

Additional assessments are usually performed which provide cross checks and further evidence regarding the likely location of any disorder in the hearing pathway. These tests are an important part of the clinical diagnostic process but were less relevant to the present study. These other tests are: tympanometry, acoustic reflex thresholds, and otoacoustic emissions. Clinical procedures for these tests were defined in NZAS (2007).

1.1.5 Alternative types of speech testing

The procedures in NZAS (2007) for speech audiometry for adults were not the only type of speech testing available. The following are some of the other types of tests available.

1.1.5.1 Word and sentence speech testing

Speech testing can measure the ability to hear and repeat words or sentences. The test procedures in NZAS (2007) were based on repeating words heard in a quiet background. The ability to repeat test sentences more closely matches real-world speech understanding situations (Sommers, Tye-Murray & Spehar, 2005).

1.1.5.2 Speech-in-noise testing

Speech testing of both words and sentences in a quiet background uses listening conditions that are experienced in a limited range of real-world listening situations. This reduces the “face validity” of

such tests. Real-world listening situations often involve listening to sentences in background noise. Background noise situations are also the situations with which people with hearing impairment report the greatest difficulty (Picou, Ricketts & Hornsby, 2013). Speech-in-noise tests can assess a person's ability to understand speech in background noise and thus, they have greater “face validity”. Results of such speech-in-noise tests are often not consistent with the pure tone and speech in quiet audiometry results and hence provide further diagnostic information (Grant & Walden, 2013).

1.1.5.3 Auditory-visual speech-in-noise testing

While speech-in-noise sentence testing more closely matches real-world listening situations than speech in quiet sentence testing, such speech testing is administered without the face of the person saying the sentences being visible. Real-world listening situations often involve listening to sentences in background noise while observing the face and lips of the person saying the sentences. Auditory-visual speech-in-noise tests can assess a person's ability to understand speech while obtaining visual information from the face and lips of the person speaking. Results of such auditory-visual tests may be able to provide further diagnostic information (Tye-Murray, Sommers & Spehar, 2007a). The present study considers the potential use of such diagnostic information for making rehabilitation recommendations.

1.1.6 Example speech-in-noise tests

Having established the desirability to test speech understanding in noise, a variety of speech-in-noise tests were available in a variety of languages (Taylor, 2011; Wilson, McArdle & Smith, 2007). The following are some example tests.

1.1.6.1 The Hearing In Noise Test

The Hearing in Noise Test (HINT; Nilsson, Soli & Sullivan, 1994) involves listening to and then repeating pre-recorded sentences in noise at various signal-to-noise ratios (SNRs). Sentence repetitions are scored as being entirely correct or entirely wrong. The speech and noise levels are varied to find the "sentence speech reception threshold" in quiet and in noise. The sentence speech reception threshold SNR is the condition under which a score of 50% correct is obtained.

1.1.6.2 The Quick Speech-In-Noise test

The Quick Speech-In-Noise (QuickSIN) test (Etymotic Research, 2006; Killion et al., 2004; Niquette, Gudmundsen & Killion, 2001) involves listening to pre-recorded sentences in noise at various SNRs. Sentences repeated by the person being tested are scored by the clinician using keyword in the sentences. The sound level of speech presented is determined based on the pure tone audiogram of the person being tested and using a loudness scaling procedure. Each sentence presented has progressively more intense background noise while the speech sound stays at the same level. The total number of key words correctly repeated provides an estimate of the additional SNR required to understand sentences by the person being tested relative to a typical normal hearing person. The QuickSIN test was available for use at the University of Canterbury Speech and Hearing Clinic (UCSHC) but was not part of the protocols defined in NZAS (2007).

1.1.6.3 Matrix sentence speech-in-noise tests

Another type of speech-in-noise test is the Matrix Sentence Test (MST). The present study used this type of test. Speech testing in noise using matrix sentences was first described in a study by Hagerman (1982). Each matrix sentence has the same grammatical structure, such as "name verb quantity adjective object" (Houben et al., 2014). An example of such a structure is "Amy has nine green shoes". In this example matrix sentence, a name such as "Amy" is always in the first place in

the sentence and an object such as “shoes” is always in the last place in the sentence. Each of the five categories of word in the sentence has 10 possible alternatives, giving 50 words in total. The relative levels of the recorded words in generated matrix sentences are adjusted to equalise their difficulty while still sounding natural. During testing, the noise level is held constant while the speech sound level is varied. The person being tested repeats back the sentences heard in noise. The word speech reception threshold SNR is the condition under which a score of 50% of words correct is obtained.

MSTs suffer from a learning effect. The performance of the person being tested improves as more lists are presented and the person becomes familiar with the sentence grammar and the word list available at each place in sentences (Hagerman, 1982; Wagener & Brand, 2005). The learning effect in matrix sentences testing can be substantially reduced by providing training prior the measurements (Wagener & Brand, 2005). Training causes performance improvement from learning to be mostly completed before scored testing begins.

Keidser et al. (2013) reported that there were many advantages of MSTs over other types of testing that make it suitable for auditory-visual testing. One advantage is that it lends itself to automated adaptive procedures for adjusting speech and noise sound levels. Automation allows for fast and sophisticated decision processes in software that improve the reliability of measurements relative to manual procedures. Another advantage is that there is only a small set of words for which visual lip movements need be video recorded. There are then a limited number of words before and after which can affect the lip movement shapes for each word being recorded. Once this limited set of sound and video recordings (typically a few hundred) has been made, up to 100,000 possible sentences can be generated.

1.1.6.4 Comparing results between different test methods

A variety of different speech-in-noise tests have been used by studies in literature. The variation in test methods makes it difficult to compare results between studies (Wagener & Brand, 2005). When comparing the results coming from differences in tests methods, Wagener & Brand (2005) found that presentation level, adaptive procedures, and different types of speech shaped noise did not significantly influence speech test results. However, the use of fluctuating noises strongly influenced the results. These test method differences should be considered when comparing results from different studies.

1.1.7 Hearing impairment rehabilitation

Once the location, possible cause, and extent of a hearing impairment have been assessed, the clinician can discuss rehabilitation options with their client (a person seeking services for assistance with possible hearing impairment). As described above, the inclusion of speech-in-noise testing and auditory-visual testing can make speech listening conditions used during the assessment align more closely with real-world listening conditions. The most appropriate option to improve communication will depend upon the hearing assessment results and also the goals, budget, and preferences of the person with hearing impairment. The available options are as follows.

1.1.7.1 Medical treatment

Some causes of hearing impairment can be treated by medical surgery or by medicines (Katz et al., 2009). In this case a medical referral is required. Middle-ear pathologies such as otosclerosis, and retrocochlear pathologies such as tumours on the vestibulocochlear nerve are examples of such conditions.

1.1.7.2 Communication strategies instruction and counselling

For nearly all causes of chronic hearing impairment the client will benefit from instruction on communication strategies. These strategies can be used on their own or along with other rehabilitation options, such as amplification. The instruction involves explaining actions the client can take to improve communication such as choosing their seating location, looking at the face of the person talking, and asserting their communication needs with communication partners (Katz et al., 2009). Counselling can be provided on how to cope with the effects of the residual hearing impairment (Boothroyd, 2007).

1.1.7.3 Auditory and auditory-visual perceptual training

Another rehabilitation option that can be used on its own or along with other rehabilitation options is "perceptual training" (Boothroyd, 2007). Such training can improve listening skills or improve the use of visual information along with improving listening (Katz et al., 2009).

1.1.7.4 Sign language

Some clients may learn sign language as a way of improving communications via an alternate path (Katz et al., 2009).

1.1.7.5 Hearing assistance technologies

Hearing assistance technologies may also be used in combination with other rehabilitation options. These technologies can improve access to the speech in a large room of people (such as a lecture hall) or from a telephone or television (Katz et al., 2009).

1.1.7.6 Amplification

Another common rehabilitation option is to amplify sound using a hearing aid or cochlear implant worn on the ear (Dillon, 2012; Katz et al., 2009). The present study considers rehabilitation using hearing aid amplification.

1.1.8 Amplification using hearing aids

Amplification using hearing aids assist the person with hearing impairment by making low intensity sounds that are inaudible louder (more intense) so that they are above the hearing threshold (Dillon, 2012; Katz et al, 2009). As described above, the pure tone audiogram shows the variation in hearing threshold as a function of sound frequency. The amplification settings of a hearing aid can be adjusted by a clinician so that most amplification is provided for the sound frequencies with the greatest hearing impairment as recommended by an amplification prescription (Dillon, 2012). This feature of modern hearing aids is one of many features that provide the person with hearing impairment with amplified sound (particularly speech) with the greatest chance of being understood (Dillon, 2012).

1.1.8.1 Limitations of hearing aids

Even with the very best of modern hearing aids amplifying and processing speech sounds, hearing aids are unable to restore normal hearing. One of the reasons for this is that inner ear hearing impairment, such as that caused by presbycusis, affects more than just the ability to detect the presence of low intensity sound. The damaged inner ear is also unable to separately detect the presence of multiple sounds whose frequencies have small differences (Dillon, 2012). This blurring together of sounds from adjacent frequency regions is perceived by the hearing impaired person as reduced speech sound clarity. Increasing sound intensity using hearing aid amplification can improve clarity to some extent by making previously inaudible frequencies audible, but the amplification does not help with the reduced clarity that comes from the blurring together of adjacent frequency regions.

This limitation to hearing aids is most noticeable when the person with hearing impairment listens to speech-in-noise.

1.1.8.2 Compensating for hearing aid limitations

The limitations of hearing aids mean that some of the other rehabilitation options mentioned above are used in combination with hearing aids to maximise improvements in communications. The complimentary option most relevant to the present study is "perceptual training" including training to improve the use of visual information.

1.1.9 Producing and understanding speech

The above describes hearing impairment and its diagnosis and rehabilitation. Before further exploring the use of diagnostic information from auditory-visual speech testing for making rehabilitation recommendations, it is helpful to analyse the nature of speech and the features of speech that people use to understand it.

1.1.9.1 Speech production

Speech sounds are made by the vocal organs along the vocal tract including the lungs, trachea, larynx containing vocal folds, throat, nose, and mouth. Two types of speech sound can be produced – voiced and unvoiced speech (Moore, 2012). Voiced speech uses vibrating vocal folds as a source having a fundamental frequency and associated harmonics. The shape of the vocal tract shapes the spectrum of harmonics. This shape has resonant peaks called formants. Detecting formants is an important part of understanding voiced speech, particularly for vowels. Unvoiced speech involves a constriction of the vocal tract that shapes the spectrum of a noise sound source. Unvoiced speech is important for many consonants although some consonants are voiced.

1.1.9.2 Place and manner of articulation

Focussing on consonants, the concepts of place and manner of articulation are important distinctions for describing the shaping of the vocal tract. The place of articulation is the point along the vocal tract where there is a stricture or obstruction. For example, this could be the tongue on some part of the roof of the mouth (Maddieson & Ladefoged, 1996). The manner of articulation refers to the configuration of the element of the vocal tract in relation to each other.

Part of the task of understanding speech is to determine the place and manner of articulation from the sounds heard. Mid to high frequency sounds provide most information about the place of articulation, mostly for consonants. Low to mid frequency sounds provide most information about the place and manner of articulation and voicing, mostly for vowels (Walden, Grant & Cord, 2001).

1.1.9.3 Phonemes and visemes

Spoken language is expressed as a series of words. Each word is made up of a sequence of sounds. The smallest units of speech sound in words are called phonemes (Moore, 2012). When looking at the face and lips of the person talking, there is visual information that is associated with each phoneme. These smallest units of visual speech are called visemes (Chen, 2001).

More than one sound phoneme is often associated with the same viseme, which makes the meaning of a viseme ambiguous. For example, the /p/, /b/, and /m/ phonemes are all produced by a closed mouth shape. They are visually indistinguishable and hence form a viseme group (Chen, 2001). As another example, the viseme group having a mouth shape where the upper teeth are touching the lower lip is for the phonemes /f/ and /v/.

Differences in speech timing and duration (seen in video) reduce the ambiguity that exists when a viseme group is observed at a single point in time (seen in a photograph) (Chen, 2001). However,

some ambiguity with regards to the phoneme uttered for a viseme group still exists. Some sounds that are acoustically ambiguous are more clearly separated by their viseme. For example, the phonemes /l/ and /r/ in English are often similar but the viseme facial expression more easily identifies which of the two phonemes was uttered.

1.1.9.4 Visual contribution to speech understanding

Observing visual information in speech results in the extraction of a sequence of visemes. Past studies have assessed the contribution of obtaining visual information in understanding speech. Visual information provides the most information about the place of articulation of consonants (Dillon, 2012; Walden, Grant & Cord, 2001). The place of articulation of consonants corresponds to mid to high frequency sounds (Walden, Grant & Cord, 2001). These frequencies are often the most difficult from which to extract information using hearing alone for hearing impaired people with common causes of hearing impairment, such as presbycusis.

Visual information provides the least information about the place and manner of articulation and voicing of vowels (Walden, Grant & Cord, 2001). Vowels typically contain low to mid frequency spectral content. These frequencies are often the easiest from which to extract information using hearing alone for hearing impaired people with common causes of hearing impairment, such as presbycusis. Hence hearing and vision provide different information and are complimentary in understanding speech (Dillon, 2012).

1.1.10 Hearing aids and vision

1.1.10.1 Is visual skill related to success with hearing aids?

Nearly three quarters of adults who could benefit from hearing aids do not own them (Dillon, 2012; Hesse, 2004). Of those who do own hearing aids, only between 60-80% wear them on a regular basis

(Laplante-Lévesque et al., 2014). In addition, adults who wear hearing aids receive varying amounts of benefit and satisfaction with hearing aids (Dillon, 2012; Knudsen et al., 2010). One of the most common complaints reported by adults with hearing impairment (with and without hearing aids) is the decreased ability to understand speech in background noise (Picou, Ricketts & Hornsby, 2013). When these adults converse in background noise, they must rely more heavily on the ability to obtain and integrate visual information with the auditory signal (Tye-Murray, Sommers & Spehar, 2007a). No published studies have researched the relationship between the ability to integrate visual information and hearing aid outcomes or candidacy. The present study begins research into this important topic.

1.1.10.2 Study of visual skill related to hearing aid outcomes

The present study used speech tests presented in the auditory-visual mode, as well as the auditory-alone mode, to measure the ability of participants to make use of visual information to understand speech. The participants were persons who volunteered to be included in the research study. The measurements were analysed in relation to measurements of participant hearing aid outcomes to see if ability to integrate visual information and hearing aid outcomes were related.

1.1.10.3 Study results may guide rehabilitation option selection

Understanding the relationships between i) hearing aid outcomes and ii) the ability to integrate visual information with auditory information, may help in determining hearing aid candidacy or assist in determining the most appropriate rehabilitation pathways, including the provision of perceptual training to improve the use of visual information.

1.2 Auditory-visual integration

The above introduced the concept of people integrating visual information with auditory sounds to improve the understanding of speech and that this may be related to hearing aid outcomes. The topic

of integrating visual information with auditory sounds is well documented in literature. A review of this literature helped to inform the design of the present study.

1.2.1 What is auditory-visual integration?

Recognising speech using auditory-visual input involves integrating the auditory and visual signals. Auditory-visual integration (AVI) is a mental process where a person combines an auditory signal and a visual signal to determine what words were said by a person speaking (Grant & Seitz, 1998). The use of AVI is not limited to persons with hearing impairment. It is used by most people who can see the lips of the person talking (Tye-Murray et al., 2010). AVI is also called "speechreading" in some literature.

This mental process of AVI is a distinct process from auditory speech perception and visual speech perception. The distinct nature of the integration process was studied by Most, Rothem, and Luntz (2009). The study enrolled three groups (N = 10) of age matched participants aged between 10 and 19 years (average = 15 years), who differed in their hearing levels. The three groups were people with: (1) severe hearing impairment, (2) profound hearing impairment, and (3) cochlear implants. The participants' speech perception was measured under three conditions – auditory-visual, auditory-alone, and visual-alone. The study showed that for word stimuli presented at low intensities, the auditory-visual speech perception scores of all three groups of participants were higher than the sum of their auditory-alone speech perception scores and their visual-alone speech perception scores. A limitation of this study was that the stimuli were presented in silence at a low sensation levels rather than in noise, and the participants were all young. However, in combination with the study by Tye-Murray, Sommers and Spehar (2007a), the study by Most, Rothem, and Luntz (2009) provides strong evidence for "integration" as a separate process from auditory speech perception and visual speech

perception. Integration provides benefits greater than simply the addition of the visual perception and auditory perception.

In agreement with the concept of integration as a separate process, most models of auditory-visual speech perception (Tye-Murray, Sommers & Spehar, 2007a) contain at least three independent mechanisms:

1. The ability to lipread (understand speech using only visual information)
2. The ability to encode auditory information
3. The ability to integrate information obtained from the two modalities (auditory and visual)

The implication of the three independent mechanisms is that studies measuring AVI (such as the present study) should measure speech perception in all three conditions.

1.2.2 Measurement of auditory-visual integration

1.2.2.1 Auditory-visual enhancement measure of integration skill

Once one accepts that AVI is a separate process from auditory speech perception and visual speech perception, one would expect some people to be better at this integration than others. A measure of this skill or ability is needed for researchers to be able to relate the integration ability of participants to other participant characteristics. This measure of ability is called "Auditory-Visual Enhancement" (AVE). The use of AVI skills while listening to speech in the unaided condition results in a measurable AVE score during speech testing. The AVE score can be expressed as the difference between the percent correct score listening to speech-in-noise at the same SNR for the auditory-visual and auditory-alone conditions (Grant & Seitz, 1998). Alternatively, the AVE score can be expressed as the difference in SNR when listening to speech-in-noise, to achieve the same percent correct for the

auditory-visual and auditory-alone conditions (MacLeod & Summerfield, 1987). The former method of expressing AVE was adopted by the present study.

The above provides the present study with guidance regarding how to measure AVE but there are additional issues regarding how to express AVE. When AVE is expressed using the "difference between the percent correct listening to speech-in-noise at the same SNR" method, a normalisation issue arises. The AVE that an individual participant may score is limited by their auditory-alone score. The traditional way of dealing with this, as explained in Grant and Seitz (1998) and Tye-Murray, Sommers and Spehar (2007a), is to express normalised AVE as:

$$AVE = (AV - A) / (1 - A)$$

where "AV" is the score in the auditory-visual condition and "A" is the score in the auditory-alone condition for an individual. "(1 – A)" is the maximum possible raw AVE for the individual given their auditory-alone score. "(AV – A)" is the measured raw AVE for the individual. The normalised AVE is the measured raw AVE relative to the maximum possible raw AVE. This way of expressing AVE was adopted by the present study.

Having determined that AVE is an important participant characteristic to measure, it is then necessary to consider factors that influence the measurement so that a suitable experiment may be properly designed. The magnitude of AVE that is expected depends on a variety of covariate factors described in section 1.8 but in particular the following factors were important to the design of the present study.

1.2.2.2 Effect of age on auditory-visual integration

In a between-groups study of 38 normal hearing younger adults (average age 20 years) and 44 normal hearing older adults (average age 70 years), Sommers, Tye-Murray and Spehar (2005) found that older adults integrate consonants and words less well than younger adults, but do as well with

sentence stimuli. The present study is interested in real-world speech recognition which mostly involves understanding sentences rather than consonants or words. The findings of Sommers, Tye-Murray and Spehar (2005) suggest that hearing threshold matched older adults should perform as well as younger adults under real-world listening conditions. There are further interactions between types of sentences and the comparative performance older and younger adults, as described in section 1.8.1.

1.2.2.3 Effect of stimulus type on auditory-visual integration

In a within group study of 41 adults of average age 66, Grant and Seitz (1998) found that the magnitude of AVE measured in tests using sentences was not significantly correlated to the enhancement measured in tests using consonants. The study stated that this finding was in dis-agreement with the findings of a number of earlier studies. However, the finding and recommendations in Rogers (2012); Sommers, Tye-Murray and Spehar (2005); and Tye-Murray et al. (2008) also suggest that AVE tests using sentences provide results that differ from tests using consonants or individual words. In consideration of all these studies on stimulus types, it can be concluded that tests intended to measure real-world AVE must use sentences rather than consonants or individual words.

1.2.2.4 Effect of noise type on auditory-visual integration

In addition to selecting the most appropriate stimulus type to measure AVE, the type of interfering noise also requires selection.

Speech babble noise (as used by the QuickSIN test) is more like real-world noise (Killion et al., 2004) but produces less consistent test results than constant noise. There are several reasons for the more consistent results provided by constant noise. The study by Stone (2016) showed that, when using the MST that was also used by the present study, the slope of the psychometric function (percentage of words correct for different SNRs) was steeper for masking with constant noise than with speech

babble noise. A test with a steeper psychometric function provides a more accurate estimate of the true speech-in-noise reception threshold (SRTn), as small changes in SNR produce large changes in the percentage of words correct. The consequences of such improved sensitivity are greater expected test-retest reliability for the same participant and a greater ability to differentiate small differences in SNR performance between participants. The results measured by Stone (2016) agree with past findings in literature. Compared to speech babble noise, constant noise was found to reduce variability, which generated improved result reproducibility (Bacon, Opie & Montoya, 1998; Killion et al., 2004).

In consideration of these studies on noise types, it can be concluded that, while speech babble noise is more like real-world noise, it is preferable to test AVE using constant noise.

1.2.3 Auditory-visual integration and hearing aids

Section 1.1.9.4 describes the perceptual mechanisms that result in visual information contributing to speech understanding that is measured as AVE. These underlying perceptual mechanisms interact with the benefits provided by hearing aids (Walden, Grant & Cord, 2001).

A within group study of 25 army audiology clinic patients with SNHI (average age 66 years) investigated the benefits of AVI and amplification (Walden, Grant & Cord, 2001). Speech testing was performed without background noise using consonants carried in VCV syllables. The study found that AVI helped speech understanding most in the mid to high frequencies (place of articulation of speech, mostly for consonants) and amplification helped most in the low to mid frequencies (place and manner of articulation and voicing, mostly for vowels). AVI provided more information on place of articulation than did amplification. This study showed that amplification and AVI were complimentary. The studies analysed in section 1.6.2 showed how amplification and AVI interact. In

consideration of all these studies, one should expect AVI ability (measured using AVE) to have some effect on hearing aid outcomes.

The interaction between perceptual mechanisms and AVE found by Walden, Grant and Cord (2001) re-enforce the likelihood that AVE is related to hearing aid outcomes. That possible relationship has not been studied in published literature and is the topic of the present study.

1.3 Auditory-visual integration in noise

The above describes AVI and its benefits without quantifying those benefits. Studies in literature have documented the expected benefits of AVI by measuring AVE in various ways under various conditions. Past studies into AVI in noise provide further guidance to the present study regarding the ideal study design.

1.3.1 Magnitude of auditory-visual enhancement in noise

A study by MacLeod and Summerfield (1987) found an average AVE for the speech reception threshold of 11 dB for normal hearing participants listening to speech in white noise. Note that the speech reception threshold is not the measure of AVE used in the present study. The range of speech reception threshold enhancement was from 6 dB to 15 dB between people and from 3 dB to 22 dB between sentences (some sentences are easier for AVI). MacLeod and Summerfield (1987) also found that AVE is highly correlated to lipreading (visual-alone) ability.

1.3.2 Magnitude of auditory-visual enhancement as a function of SNR

The size of the AVE has been shown to vary with the SNR of the signal being heard. Ma et al. (2009) studied 17 young university students with normal hearing and vision in a within group study. The study showed a peak enhancement (averaged across participants) at a SNR of -12 dB. This resulted in

an improvement from an average of 15% of words correct for the auditory-alone condition to 60% correct for auditory-visual condition (i.e. a raw AVE of 45%). In addition to providing the largest enhancement, this test condition also avoided ceiling effects in the auditory-visual condition by providing head room for most participants (Wu & Bentler, 2010b). These findings provide guidance to the present study by suggesting that measuring AVE at a SNR where participants achieve approximately 15% of words correct in the auditory-alone condition, maximises the size of the measurement (hence reducing the influence of random errors) and prevents ceiling effects.

1.4 Auditory-visual integration and hearing impairment

The relationship between AVI and hearing aid outcomes has not been studied in literature and the present study begins research into this topic. However, the relationship between AVI and hearing impairment has been well documented in literature. In particularly, studies often focussed on the relationship between AVI and the hearing disability caused by the hearing impairment. Understanding these relationships helps to provide a rationale for the present study and may help in guiding its design.

1.4.1 Auditory-visual integration effect on hearing disability

When adults with hearing impairment converse in background noise, they must rely more heavily on the ability to obtain and integrate visual information with the auditory signal (Tye-Murray, Sommers & Spehar, 2007a). This was further demonstrated by the finding that, AVE was the second most important factor in hearing disability found in a within group study of a representative sample (N = 56, average age 51 years) of adults with SNHI by Corthals et al. (1997). This study is further analysed below but the author of the present study's summary of the findings is that people with hearing impairment rely on AVE to limit hearing disability.

The term “hearing disability” is best explained using examples. Examples of hearing disability are activity limitations such as difficulty understanding conversation and difficulty understanding television (Hickson et al., 2008). The related term “hearing handicap” is also best explained using examples. Examples of hearing handicap are participation restrictions such as not attending social situations like family dinners or club functions (Hickson et al., 2008).

Corthals et al. (1997) found that the top four factors affecting real-world self-reported hearing disability were as follows:

1. Better ear speech reception threshold (SRT),
2. AVI ability (AVE),
3. Better ear pure tone average (PTA),
4. Noise susceptibility (noise impact on SRT).

Not that the author of the present study assumes that hearing disability was self-reported for the unaided condition rather than for the aided condition, but this was not explicitly stated by Corthals et al. (1997).

The study found that removing factors 3 and 4 above had little effect on correlation of predicting disability. Better ear PTA (factor 3) is related to SRT (factor 1), which is why PTA can be dropped as a predictor. It was less clear why noise susceptibility (factor 4) was not important, but the study found that it did correlate with other predictors and hence this made it appear less independent. Corthals et al. (1997) found that only factors 1 (SRT) and 2 (AVE) need be considered to predict real-world

hearing disability. This further emphasises the importance of studying AVE and its possible effect on hearing disability after hearing aid are fitted.

1.4.2 Auditory-visual integration test to predict hearing disability

Another implication of the above finding of "noise susceptibility" not being important to predict hearing disability, is that the QuickSIN test may be less valuable than an auditory-visual test to measure the hearing handicap that hearing aids seeks to improve. Robertson, Kelly-Campbell and Wark (2012) studied 144 people with SNHI split into three groups based on hearing aid purchase decisions and usage patterns. They found that SNR loss measured by the QuickSIN test was the best predictor of hearing aid purchase and usage (which is not the same as disability) in the first year following hearing aid purchase. This finding around "usage" is important because Humes et al. (2001) have shown that "usage" is one of the seven independent outcomes that explains most of the variation in self reported hearing aid outcomes. Considering all these findings together, AVE testing should provide even more information about hearing disability and possibly about hearing aid outcomes, than SNR loss measured by the QuickSIN. This provides further evidence for the need to research the relationship between AVE and hearing aid outcomes.

1.4.3 Effect of hearing impairment on auditory-visual integration

The above explains that hearing impaired adults rely on AVI to reduce their hearing disability. This raises the question about whether the presence of hearing impairment causes people to practise AVI more often and become better at AVI. This question has been researched with some conflicting findings.

In a between groups study, Tye-Murray, Sommers and Spehar (2007a) tested two groups of older adults' sentence recognition abilities using varying SNRs for the auditory-alone and auditory-visual

conditions. One group (N = 53, average age 73) had normal hearing and the other group (N = 24, average age 74) had mild to moderate hearing impairment. The study found that older adults with hearing impairment do not have better visual-alone speech perception or AVI ability than age matched older adults with normal hearing. Tye-Murray, Sommers and Spehar (2007a) stated that the tested listening conditions were not real-world listening conditions and this limited their ability to generalise the findings to the two populations.

1.4.3.1 Effect of hearing impairment onset age on auditory-visual integration

A between groups study by Tillberg et al. (1996) using two groups of 10 participants with bilateral SNHI, found that acquiring hearing impairment did not result in improved AVI ability unless the impairment was acquired at an early age. Visual-alone (lipreading) speech understanding scores were better for the early onset group (average age 46 years with PTA of 68 dB HL). Visual-alone skills were shown to be best learnt before the age of 8 years. After the age of 16 years it was difficult to improve visual-alone skills. However, the early onset group had worse hearing (severe impairment) and hence might have relied on vision more due to worse hearing rather than due to early onset, when compared to the late onset group (moderate hearing impairment, average age 53 with PTA of 39 dB HL).

Tillberg et al. (1996) also found that the late onset group did not benefit from using hearing aids in noise to understand speech compared to using no hearing aids at all. The early onset group did benefit from using hearing aids in noise to understand speech. The benefit experienced by only the early onset group could possibly be produced by both their superior visual-alone skill or by their worse hearing (PTA) requiring the use of hearing aids more than the better hearing late onset group. Such uncertain findings provide further evidence for the need to research the relationship between AVE and hearing aid outcomes.

Conflicting with the research mentioned above from Tillberg et al. (1996) regarding AVI and hearing impairment onset age, is the research from Kyle et al. (2013). This between groups study of 86 deaf children (defined by the study as severe-to-profound hearing impairment) and 91 children with normal hearing, showed that AVI improved with age through childhood and into teenage years and was the same at each age for deaf and normal hearing children. This conflicts with the idea of early onset (before age 8) hearing impairment resulting in better AVI. However, it could be that the deaf children in this study had insufficient residual hearing and that any superior AVI performance for people with early onset hearing impairment is for those with more residual hearing.

1.5 Auditory-visual integration and perceptual training

The above review of literature and analysis has only considered possible relationships between AVI ability (measured using AVE) and hearing aid outcomes. Hearing aids are only one of the rehabilitation options for people with hearing impairment. As described in section 1.1.7.3, another potentially worthwhile rehabilitation option is “perceptual training”. It is possible that measuring AVI ability may provide a diagnostic benefit that may guide perceptual training options as well as hearing aid use. Literature provides some relevant findings on this topic.

Research suggests that persons with a downward sloping SNHI receive the maximum benefit from AVE and receive the minimum benefit from amplification for understanding speech (Grant & Seitz, 1998; Tillberg et al, 1996). Such hearing impairment configurations are common amongst older adults. This raises the question about whether improving a person's AVI skills (resulting in a larger AVE) could be a useful form of rehabilitation. If so, then testing clinic clients' AVE could be a factor in determining appropriate rehabilitation strategies.

1.5.1 Training for improved auditory-visual integration

It could be that perceptual training to improve AVE might be a rehabilitation strategy instead of hearing aids or complementing hearing aids. Tye-Murray, Sommers and Spehar (2007a) found that auditory-visual and visual-alone speech tests provided diagnostic information important for designing the most effective audiological rehabilitation strategies.

Improving the AVE of a person with hearing impairment using training could be an appropriate rehabilitation strategy only if such training has been shown to be effective. In a within group army audiology study of 29 adults aged between 41 and 88 years (average age 65) with acquired SNHI, Grant and Seitz (1998) showed that, in theory, AVI training could improve auditory-visual consonant recognition by 26%.

Lonka (1995) studied 76 working age adults in a randomised controlled trial of between group interventions. The study showed that both face-to-face instructor-lead (high cost) AVI training and home-based video (low cost) self-training improved AVI skills similarly. The training improved test scores in this study from 28% to 38%. Measuring AVE in audiology clinics might be able to identify candidates for such low cost video training.

The conclusion that the author of the present study draws from these studies is that AVI is a skill that can be improved by training and training could be part of a rehabilitation strategy. Such training could be recommended based on the results of auditory-visual testing.

1.5.2 Selecting rehabilitation pathways

A study by Grant, Walden, and Seitz (1998) has already considered rehabilitation pathways that might be recommended based on auditory-visual testing results. Future clinical protocols for rehabilitation pathways proposed by Grant, Walden, and Seitz (1998) are shown in Table 1.

Test Results	Rehabilitation
Poor auditory-alone performance	Hearing aids
Poor visual-alone performance	Wear eye glasses
Poor AVE	Auditory-visual training and practice
Poor top down language guessing	Language training

Table 1. **Rehabilitation pathways**

In consideration of all of the above studies, it seems that measuring AVE may provide useful information for the design of maximally effective rehabilitation strategies, including perceptual training. Such a possibility provides further rationale for the present study and future related studies that can investigate diagnostic applications of auditory-visual testing.

1.6 Studies of auditory-visual integration and hearing aid outcomes

AVI and AVE have been extensively researched by studies in published literature However, these studies did not measure the relationship between AVE and hearing aid outcomes. Typically they measured the relationship between AVE and unaided hearing disability. Studies by Erber (2002), Rogers (2012), and Tye-Murray, Sommers and Spehar (2007a) speculate about the significance of AVE for rehabilitation strategies (such as hearing aid provision) without actually measuring the significance. No published studies have researched the relationship between AVE and hearing aid outcomes or candidacy.

Published literature contains speculation regarding data related to the relationship between AVE and hearing aid outcomes but without measuring hearing aid outcomes directly or stating the expected direction of the relationship. For example, one could interpret the study by Tillberg et al. (1996) as suggesting that better AVE could result in better hearing aid outcomes. The study found that people with better visual-alone speech recognition had better auditory-visual speech understanding in noise

when using hearing aids compared to unaided. In contrast, people with poorer visual-alone speech recognition understood speech-in-noise in the auditory-visual condition the same with or without hearing aids. From this data, one would expect that the group with better visual-alone understanding of speech would perceive more benefit from hearing aids. One could then speculate that the group with better visual-alone speech understanding would also have a greater AVE that would be related to better hearing aid outcomes. Unfortunately, this difference in hearing aid outcomes was only measured in relation to visual-alone speech understanding, and can also be explained by other differences between the study's participant groups. In particular, the group with better visual-alone performance had early onset hearing impairment and had worse hearing thresholds that were expected to benefit more from amplification.

Contrary to Tillberg et al. (1996), a study by Erber (2002) concluded that many people with adequate vision can compensate for a high frequency hearing impairment using AVI in face-to-face communication and that this precluded the need for hearing aids. This implies that better AVE would result in lower hearing aid benefit. Such conflicting speculation helps to justify the need to directly measure the relationship between AVE and hearing aid outcomes (the topic of the present study).

"Erber's area" (Erber, 2002) was the name given to the area of the audiogram up to 1000 Hz and more than 50 dB HL, which Erber claimed was a predictor of hearing aid candidacy. Erber claimed that, if the audiogram of a person with hearing impairment passed through Erber's area, this made them a good candidate for a hearing aid. Erber claimed that the size of Erber's area was substantially affected by AVI ability. Erber claimed that poor AVI ability could increased the size of Erber's area on the audiogram into higher frequencies (up to 4 kHz) and to lower sound intensities (down to 35 dB HL). Erber speculated that the combination of the audiogram and measuring AVE would predict hearing-aid candidacy.

The within-group study by Erber (2002) used a large number of participants (N = 248) but did not provide sufficient details about its methods, such as the way that conversational fluency (a proxy for speech recognition) was objectively measured. The study used visual acuity as a proxy for visual-alone speech understanding ability instead of measuring visual-alone ability or AVI ability directly. This study was also considered by Robertson, Kelly-Campbell and Wark (2012) who found that few of their participant audiograms fell into Erber's area and hence Erber's area was not a practical tool for predicting hearing aid candidacy. The limitations of the Erber's area concept found by Robertson, Kelly-Campbell and Wark (2012) has limited applicability to the present study because Robertson, Kelly-Campbell and Wark (2012) did not use the full definition of Erber's area described in the study by Erber (2002). The full definition in Erber (2002) included enlargement of Erber's area based on poor AVI ability. AVI was not relevant to the study by Robertson, Kelly-Campbell and Wark (2012) and hence the full definition of Erber's area from Erber (2002) was not used.

An alternative interpretation of the studies by Erber (2002) and Tillberg et al. (1996) is that AVE may have an opposite relationship with hearing aid benefit than it does with hearing aid satisfaction. In this case, the hypothesis for the satisfaction outcome would be that better AVE would be associated with higher hearing aid satisfaction. People with higher AVE would hear better than people with lower AVE while aided in noise, due to their ability to integrate visual information and hence were more satisfied with their aided hearing. In contrast, the hypothesis for the benefit outcome would be that lower AVE would be associated with higher hearing aid benefit. People with lower AVE would be more dependent on hearing aids due to their inability to use visual information when unaided and hence have a greater reduction of hearing disability (higher benefit) when using a hearing aid. There is insufficient evidence in published research to justify either of these speculative hypotheses for benefit and satisfaction outcomes. The present study begins the process of gathering data that can show how AVE is related to hearing aid outcomes. The findings of the present study were limited to

relationships that could be shown using the retrospective design used for the study. Carefully designed future studies using prospective and retrospective designs might be able to answer more detailed research questions about different hearing aid outcomes such as benefit and satisfaction.

1.7 UC auditory-visual matrix sentence test

The above has established the potential importance of beginning research into the relationship between AVE and hearing aid outcomes. A test tool is required to perform such research on participants and, if clinically significant relationships are established, to perform routine testing of clients in audiology clinics. The present study had access to such a test tool.

A team of researchers at the University of Canterbury (UC) developed the University of Canterbury Auditory-visual Matrix Sentence Test (UCAMST) in New Zealand English (O'Beirne et al. 2015; Trounson, 2012). This test is the first of its kind using the matrix sentence format and could make routine the clinical assessment of an audiology client's AVE.

1.7.1 Purposes for using the UC auditory-visual matrix sentence test

The present study made use of the UCAMST for several purposes:

1. To measure AVE and visual-alone performance so that they could be related to hearing aid outcomes. This was the main purpose of the present study,

2. To measure SNR loss to help evaluate if the UCAMST could replace the QuickSIN test in routine clinical test protocols,

3. To provide practical usage evaluation to the developers of the UCAMST regarding any issues which arose with using the tool in a clinical environment. This feedback was provided verbally while using the test tool and is detailed within the text of this thesis.

The above second purpose for using the UCAMST made the QuickSIN test particularly relevant to the present study. Evaluating the UCAMST's ability to replace the QuickSIN test required that the present study also test participants with the QuickSIN. In previous studies and as described in section 1.4.2, QuickSIN test results were found to be the best predictor of some hearing aid outcomes. This made the QuickSIN test tool a relevant comparison tool to the UCAMST for the present study.

1.7.2 Why use the UC auditory-visual matrix sentence test

As described above, it is reasonable to suggest that auditory-visual integration must be tested using sentences rather than words or consonants to maximise the similarity to real-world use of AVI. The UCAMST was the only available tool that could do such testing in noise using New Zealand English. Examples of test tools that have been available were discussed in the following references: Grant and Seitz (1998); Katz et al. (2009); Most, Rothem, and Luntz (2009); and Rogers (2012).

1.7.3 Description of the UC auditory-visual matrix sentence test

The version of the UCAMST used for the present study ran on a laptop computer running Microsoft Windows XP. The laptop screen was only visible to the researcher. A sound card produced sound presented to research participants using headphones. A second screen could display the face and moving lips of the person speaking and was visible to both the researcher and the participant.

The version of the UCAMST used for the present study was evaluated by Stone (2016) to ensure that the normalisation process has been successful and that the generated test lists were equivalent (i.e. equally difficult in noise).

1.7.4 Features of the UC auditory-visual matrix sentence test

The following describes UCAMST features that were relevant to the present study and explains how those features were used for testing participants. Understanding these features was a prerequisite to designing the present study.

1.7.4.1 Participant training and loudness scaling features

The UCAMST provided features that allowed the researcher to demonstrate matrix sentence sounds to participants before formal testing began. The sound levels for the right and left ears could be set independently, as shown in Figure 1. The researcher could then play example matrix sentences to the right or left ears and could play example masking noise to the right or left ears. The masking noise was constant (i.e. unmodulated) speech weighted noise. Speech babble noise was also available, but was not used. Constant noise has been shown to produce more consistent test results than speech babble noise (see section 1.2.2.4).

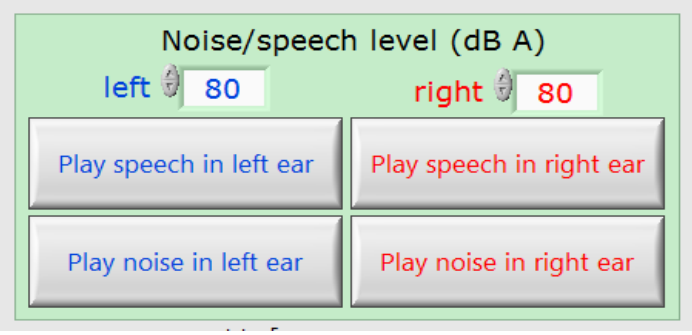

Figure 1. **UCAMST loudness setting controls**

The "recommended sound level" at which sentences were presented needed to be determined for each participant. The approach used to calculate the recommended sound level is described in section 1.9.4.5.

The study by Stone (2016) showed how percent correct scores varied with SNR (mean intelligibility functions) for normal hearing listeners. That study was not yet available when the present study was being designed. The author of the present study's experience with the UCAMST showed that the typical maximum reduction in the speech sound level (while the noise sound level remained unchanged) was about 15 dB below the recommended sound level setting (the sound level setting is also the noise sound level). In order to be testing speech-in-noise at a particular SNR, the speech must be audible in quiet at that signal level. Hence speech produced by the UCAMST must be clearly audible at 15 dB below the sound level setting for each ear, to ensure that speech is always audible in quiet.

The sound demonstration features of the UCAMST allowed the researcher to verify the appropriateness of the sound level that was intended to be used for the auditory and auditory-visual tests. Matrix sentence speech samples (randomly generated) and masking noise sound were presented to participants at various volume levels to verify audibility and comfort. The starting point for these trials was to present speech samples at the recommended sound level and also at a sound level 15 dB below the recommended sound level. These loudness scaling trials also served as training experience for the participant to repeat back matrix sentences heard. Such matrix sentence listening and repetition training varied from the scored MSTs due to the absence of the masking noise that was present in scored testing. The UCAMST demonstration features only allowed matrix sentence speech sound and masking noise sound to be presented separately.

1.7.4.2 Adaptive testing features

The UCAMST tests speech recognition in the auditory-alone, auditory-visual, or visual-alone modes. In the auditory-alone test mode, the software runs dual adaptive tracks to calculate the SNR that result in the participant scoring both 20% and 80% correct in the auditory-alone condition. These measured

SNR levels can then be applied in a fixed manner to allow measurement of the AVE achieved when the visual component of the stimuli is visible to the participant. The adaptive procedures fix the noise sound level and vary the speech sound level.

1.7.4.3 Scoring features

The UCAMST provides the researcher with two ways of scoring the matrix sentences repeated by participants. One way has the participant self-score. Self-scoring is done on a screen display that appears after a matrix sentence is heard. The display has a column for each of the five words heard. Each column shows the ten possible words that could have been heard at that position in the five-word sentence, as shown in Figure 2. The participant uses a mouse to select the word they thought they heard for each of the five columns. This approach is called “closed set” because the participant is shown the total set of possible sounds they could have heard.

Figure 2. **UCAMST self-scoring screen**

One problem with using the closed set approach with elderly participants is that the combination of holding the sentence in short-term working-memory (Brehmer, Westerberg & Bäckman, 2012) and selecting words they heard, may result in the participant forgetting the sentence before they have selected all the words. For these participants, the other way of scoring called “open set”, may present a lighter cognitive load. For the open set testing and scoring approach, the participant repeats out loud the five-word matrix sentence they thought they heard. The researcher scores which words were correctly repeated by the participant, as shown in Figure 3. In this mode of operation, the participant

needs to be trained to say out loud a best guess for as many of the five words presented to them as possible. This mode of scoring was judged to be more practical for research participants in the present study, as it may reduce the extent to which the test result would be affected by the participants' working and short term memory skills.

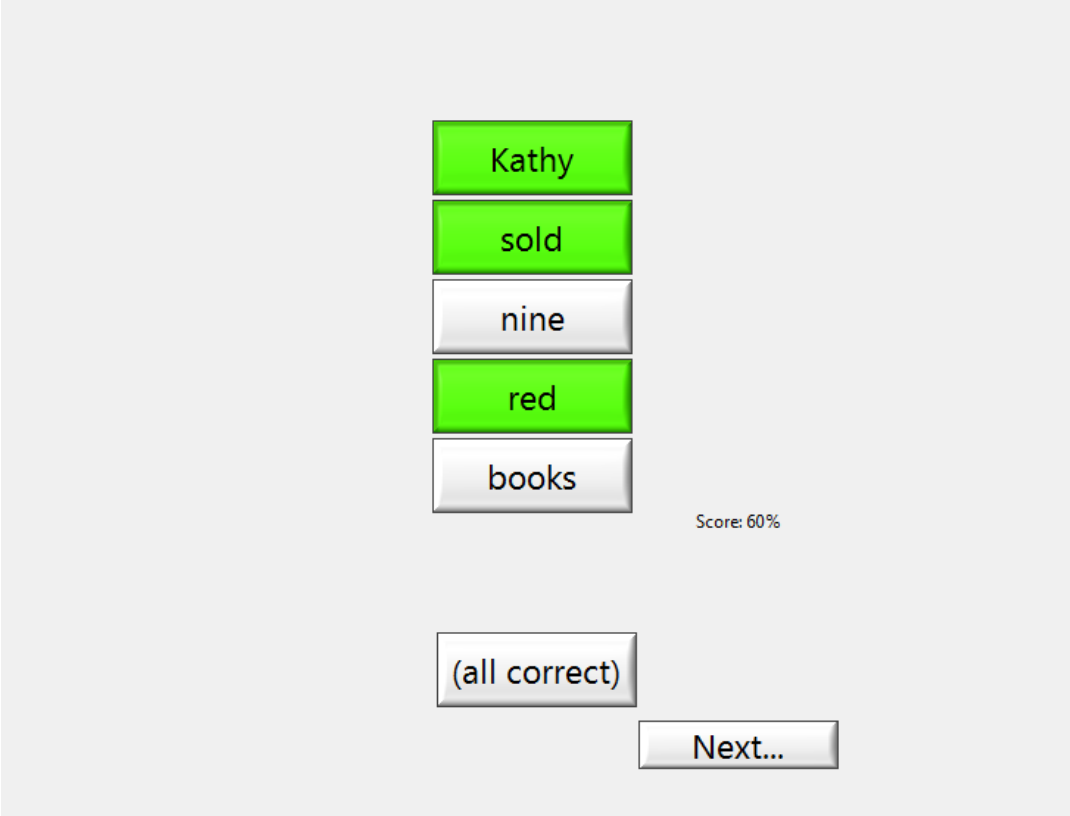

Figure 3. **UCAMST researcher scoring screen**

1.8 Control covariates

The above describes literature reviewed to help inform the design of the present study. However, even a well-designed study is typically unable to completely isolate the predictor and outcome variables from other variables that also have an affect on results. These other variables are the covariate variables that should be measured and their effect controlled.

The present study controls for a number of covariates that could affect the relationship between the predictor variable (AVE) and the outcome variables (hearing aid outcomes). Some covariates have been shown in literature to be related to outcome variables and need to be measured to statistically control for their effect on the outcome variables. This allows the unique contribution of the predictor variable on outcome variables to be estimated. Some control variables have been shown in literature to be related to the predictor variable. These need to be measured because they may have an effect on outcome variables via their effect on predictor variables. For example, if visual acuity eye chart test results are related to AVE, and if AVE is related to hearing aid outcomes, then eye chart test results may also be related to hearing aid outcomes. If that were the case, then eye chart test results could be a predictor variable that is as useful but simpler to measure than AVE.

The following are control covariates that were measured in the present study. The requirement to measure these covariates was based on a review of published AVI studies. The existence of these covariates also affected the design of the present study, as described below.

In addition to the below measured covariates, the literature review identified additional covariates that should have been measured but were not measured for logistical reasons. These unmeasured covariates would have been too difficult to measure or would have added too much additional testing time to participant test appointments. The unmeasured covariates are described in the section 4.7.

1.8.1 Age covariate

There is a relationship between a person's age and the study predictor variable AVE. Older adults' AVE is only as good as younger adults' AVE for high context sentence stimuli that allow for top down word guessing. Real-world sentences are high in context but the UCAMST uses low context sentences. Only adults aged 60 years and above were enrolled into the study to reduce the effect of

age variation on measured outcomes. The need for this control variable can be found in studies by Sommers, Tye-Murray and Spehar (2005); Tye-Murray, Sommers and Spehar (2007a); Tye-Murray et al. (2008); and Tye-Murray et al. (2010).

1.8.2 Signal-to-noise-ratio loss covariate

There is a relationship between a person's SNR loss measured by the QuickSIN and the hearing aid outcomes of purchase and usage (Robertson, Kelly-Campbell & Wark, 2012). The SNR loss of study participants was measured using the QuickSIN test for two purposes:

1. As a control covariate,

2. To compare results to SNR performance measured by the UCAMST used in the auditory-alone mode. If the results are similar then this suggests that, in addition to providing new auditory-visual test data, the UCAMST could also replace the QuickSIN test tool.

1.8.3 Asymmetric hearing covariate

Asymmetric hearing can affect various predictor and outcome variables when studying binaural speech understanding. It is common practice in audiological research to screen participant's for asymmetric hearing to control for this covariate. For example Sommers, Tye-Murray and Spehar (2005) screened for asymmetry defined as greater than 10 dB threshold difference between the two ears at any of the test frequencies. Wu and Bentler (2010a) screened at 15 dB threshold difference. Walden, Grant and Cord (2001) screened at 20 dB threshold difference. The present study could have only enrolled participants whose hearing threshold asymmetry was up to 15 dB at any test frequency. However, this restriction on enrolling participants would have reduced the participant pool size and is not strictly required for the present study. Unlike, the past studies mentioned from literature, the present study is relating bilateral hearing aid outcomes (fitted by prescription to each ear's individual

hearing impairment) to AVE (measured using loudness scaling to each ear based on a hearing aid fitting prescription). Hence, both the outcome variables and the predictor variable have compensation for asymmetric hearing to the extent recommended by a hearing aid fitting prescription (see section 1.9.4.5). Hence, candidate participants with asymmetric hearing impairment were not screened out and were invited to participate in the present study.

1.8.4 Cognitive skills covariate

There is a relationship between a person's cognitive skills and the study predictor variable AVE. Some past studies into speech reception screened for dementia using the Mini-Mental State Exam (MMSE) (Wu & Bentler, 2010a). A better screening test that detects mild cognitive impairment is the Montreal Cognitive Assessment (MoCA) questionnaire described in Nasreddine et al. (2005). Tests for dementia such as the MMSE were shown to be poorly related with speech reception ability by Akeroyd (2008) in a review of 20 previous studies. In contrast, the controlled between groups study of 277 participants by Nasreddine et al. (2005) showed that the MoCA had a 90% sensitivity in detecting mild cognitive impairment compared to 18% for the MMSE, while maintaining an excellent specificity of 87%. The present study used the MoCA questionnaire to measure mild cognitive impairment.

The cognitive skills most strongly related to the study predictor variable AVE are “processing speed” and “working memory” (Desjardins & Doherty, 2014; Grant & Seitz, 1998; Picou, Ricketts & Hornsby, 2013). In particular “working memory” has been shown by many studies to be the most important cognitive skill that predicts speech recognition in noise ability (Arlinger et al., 2009; Arehart et al., 2013; Foo et al., 2007; Lunner, Rudner & Rönnberg, 2009; Ng et al., 2013).

The Reading Span Test (RST) has been shown to be the best measure of "working memory" that predicts speech recognition in noise (Akeroyd, 2008). The original RST was defined by Daneman and Carpenter (1980). The University of Notre Dame (UND) memory laboratory gave permission for the present study to use UND RST sentences used in UND memory laboratory research studies.

1.8.5 Visual acuity covariate

There is a relationship between a person's visual acuity and the study predictor variable AVE. Past studies into AVI often screened for visual acuity using a Snellen eye chart (Desjardins & Doherty, 2014; Grant & Seitz, 1998; Katz et al., 2009; Tsaousis et al., 2013; Tye-Murray et al., 2008; Tye-Murray et al., 2010). These studies performed eye tests using vision in the mode normally used by participants for AVI, which is binocular (corrected if needed) and at a distance. Some studies screened at a Snellen eye chart result of 20/30 feet (6/9 metres) and some screened at 20/40 feet (6/12 metres). The present study had insufficient participants to be able to exclude participants for having vision worse than 20/40 feet (6/12 metres). Instead, Snellen eye chart vision testing scores were used as another control covariate.

The present study defined vision at a distance based on the study by Tsaousis et al. (2013) that defined vision distances as:

- 4 m: Distance visual acuity,
- 66 cm: Intermediate visual acuity,
- 33 cm: Near visual acuity.

Most real-world AVI occurs at distances in excess of 66 cm and hence requires visual acuity measurement for distance rather than near or intermediate visual acuity. The Snellen eye test

measures visual acuity at distance. Gagné et al. (2006) tested AVI at a minimum distance of 1.83 metres (6 feet) and a maximum distance of 7.32 metres (24 feet). Snellen eye tests for the present study were performed at a distance of 6.10 metres (20 feet) and the present study used the UCAMST with the participant's eyes being 1.1 metres from the screen for auditory-visual and visual-alone tests. The UCAMST test distance of 1.1 metres was selected to ensure that the participants used their distance vision (did not need reading glasses). At the same time, testing at 1.1 metres allowed the UCAMST's smaller than typical on the screen face size (see section 4.7.12.7 regarding the 60% face size limitation of the present study), to be of similar size and resolution as a real human face would be at conversational distances of 1.83 metres or more.

The study by Jordan and Sergeant (2000) showed that auditory-visual speech understanding was unaffected by increases in viewing distance between 1 and 10 metres. Hence, the 60% head size, viewed at 1.1 metres, in the present study should not affect auditory-visual and visual-alone test results relative to results expected from viewing a 100% head size at between 1 and 10 metres.

The combination of testing participant visual acuity at a distance using a Snellen eye chart and selecting a UCAMST auditory-visual and visual-alone test distance of 1.1 metres, allowed the visual acuity covariate to be controlled.

1.8.6 Native language covariate

There is a relationship between a person's native language and the results from speech reception testing in English. Studies in literature screened for participant native language (Grant & Seitz, 1998 ; Wu & Bentler, 2010a). The present study only enrolled participants who spoke English well and also recorded whether participants were childhood native English speakers as a check that might help explain any outlier results.

1.8.7 Gender covariate

There may be a relationship between a person's gender and the study predictor variable AVE. Some studies showed a gender effect, such as the between groups (N = 66) study by Irwin, Whalen and Fowler (2006) and the study by Strelnikov et al. (2009). Some studies showed no gender difference, such as the between groups (N = 122) study by Tye-Murray, Sommers and Spehar (2007b). The present study sought to enrol an equal number of males and females to control for possible gender effects.

1.8.8 Age of hearing impairment onset covariate

There may be a relationship between a person's age of hearing impairment onset and the study predictor variable AVE. Onset ages below 8 (and possibly up to 16) years may be related to larger AVE (Kyle et al., 2013; Tillberg et al., 1996). The present study asked participants for their estimated age of hearing impairment onset and recorded this data for statistical analysis control purposes.

1.8.9 Visual-alone speech understanding covariate

There is a relationship between a person's visual-alone speech understanding ability and the study predictor variable AVE (Tye-Murray et al., 2010). The present study used the UCAMST to test participant's visual-alone speech understanding ability. Measuring this variable allowed it to be analysed in relation to other variables in the present study and to be compared to measurements reported by studies in literature.

Visual-alone speech understanding is not an extraneous variable from the study predictor variable AVE. Hence, even though it was a covariate of interest to be analysed, it was not measured for the purpose of statistically controlling the relationship of AVE to other variables.

1.8.10 Central nervous system events covariate

There may be a relationship between a person's history of central nervous system (CNS) events and use of CNS medication, and the study predictor variable AVE (Tye-Murray et al., 2008). Examples of CNS events are stroke, concussion, head injury, and being rendered unconscious or dizzy. The present study asked participants about their CNS event history and medication use in a questionnaire.

1.8.11 Hearing aid technology covariate

There is a relationship between various hearing aid technology features and settings, and the ability of hearing aid users to understand speech-in-noise. The present study collected the following information from participant UCSHC files to make it possible to control for the hearing aid technology covariate:

- Hearing aid brand, model and style,
- Amplification prescription,
- The technology features enabled in the hearing aid,
- Hearing aid setting information (e.g. acclimatisation percentage, etc.).

The following are several examples from literature of hearing aid features that affect the ability of hearing aid users to understand speech-in-noise.

Ricketts and Hornsby (2006) and Wu and Bentler (2010a) showed an interaction between vision and directional microphones.

Both Dillon (2012) and a small (N = 12) within group intervention study of adults (median age 66) with bilateral SNHI by Desjardins and Doherty (2014) showed that noise reduction technology improved listening comfort and reduced listening effort (without improving speech intelligibility) and hence made hearing aid users more satisfied with their hearing aid.

In a small (N = 11) within group intervention study of adults aged 45 to 80 years with severe to profound SNHI, Sakamoto et al. (2000) found that hearing aid frequency compression interacts with AVE. Frequency compression hearing aids were more beneficial for hearing impaired persons with better visual-alone speech understanding ability.

Ching, Dillion and Byrne (1998) (within group study, N = 54) and Hogan and Turner (1998) (small within-group study, N = 14) showed that high frequency (4 to 8 kHz) amplification for severe and profound hearing impairment can reduce intelligibility. As explained in section 1.1.9.4, such hearing aid users with high frequency hearing impairment rely on AVI. The amount of high frequency amplification provided by a hearing aid depends upon the prescription chosen and fitting procedure to prescription. Hence data about prescription and fitting procedure were collected from participant files for the present study.

1.9 The present study

The present study related the predictor variable AVE to the outcome variable hearing-aid outcomes in participants who already used hearing aids. The study was designed to measure these variables in a way that took into consideration the background issues and covariates described above, while at the same time fitting within research study's logistical constraints. The following explains why the protocols listed in the Methods chapter were selected and designed in the way they were, among various options that could alternatively have been used.

1.9.1 Approach for measuring hearing aid outcomes

Hearing aid outcomes were not measured in a laboratory. It was more important to understand real-world experience with hearing aids as recommended by the expert opinion of Cox (2003). Instead, self-assessed questionnaires were used to measure outcomes. The questionnaires measure the success of the hearing aid in providing benefits that assist with activity limitations and participation restrictions (Helvik et al., 2006). Hearing impairment in itself does not prompt people to acquire and use hearing aids; rather it is the activity limitations and participation restrictions that it imposes on them (Robertson, Kelly-Campbell & Wark, 2012).

1.9.2 Which hearing aid outcomes should be measured?

There were many hearing aid outcomes variables that could have been measured by the present study. A literature review was conducted to determine which outcome variables were the most important to measure.

In a within group study of 173 adults aged 60 to 89 years (average age 73) with symmetric gently sloping SNHI, Humes et al. (2001) considered 26 hearing aid outcomes. The study showed that 7 of the 26 outcomes independently account for 70% of outcome variation. In importance order these were:

1. Subjective benefit and satisfaction (22.7%),
2. Aided performance (speech recognition and hearing handicap 12.2%),
3. Hearing aid use (11.6%),
4. Objective benefit for soft or conversational speech (7.5%),

5. Speech communication at high levels in noise (6%),

6. Reduction of hearing handicap (5.8%),

7. Judgement of sound quality (4.9%).

These seven outcomes provided guidance regarding the hearing aid outcomes that should be measured in the present study. The hearing aid outcomes that were chosen as requiring measurement in the present study were at least the following:

- Hearing aid benefit,
- Psycho-social quality of life (to capture emotional outcomes that might come from ease of listening or be side effects of more usage),
- Hearing handicap (or its reduction),
- Hearing aid usage.

1.9.3 Tools to measure hearing aid outcomes

Having determined the minimum set of hearing aid outcomes that required measurement in the present study, tools for measuring these outcomes were selected.

Self-report was used to measure hearing aid usage. This avoided the technical and logistical complications that would arise from attempting to read usage data logging across a wide range of hearing aid brands and models.

The International Outcomes Inventory for Hearing Aids (IOI-HA) questionnaire was chosen to measure all other hearing aid outcomes (hearing aid benefit, psycho-social quality of life, and hearing handicap). The IOI-HA was developed by Cox et al. (2000). The IOI-HA contains seven questions, one for each sub-scale. The eighth question classifies the participant's unaided hearing impairment. The IOI-HA does not require the questionnaire to be administered to research participants before and after a hearing aid fitting. This was compatible with the retrospective (see section 1.9.4.1) nature of the present study and was a major initial screening factor in selecting this questionnaire for the present study.

Smith, Noe and Alexander (2009) showed the interpreted meanings of the IOI-HA questions 1 to 7 as follows:

1. IOI-HA-Q1 - Hours of daily use (USE),
2. IOI-HA-Q2 - Benefit (Ben),
3. IOI-HA-Q3 - Residual activity limitations (RAL),
4. IOI-HA-Q4 - Satisfaction (Sat),
5. IOI-HA-Q5 - Residual participation restrictions (RPR),
6. IOI-HA-Q6 - Impact on others (Ioth),
7. IOI-HA-Q7 - Quality of life (QoL).

The outcome IOI-HA-Q1 was similar to the self-report used to measure hearing aid usage. The difference was that self-report was measured in hours whereas IOI-HA-Q1 had response categories with each category being a range of hours of hearing aid usage.

The IOI-HA has been used extensively in audiological research. In a within group study of 154 adults (average age 77 years), Cox et al. (2003) conclude that the IOI-HA is brief by design but general enough to be appropriate in many different study types.

Smith, Noe and Alexander (2009) studied 131 males (average age 74 years) who had used hearing aids for more than six months. The study confirmed the desirable attributes of the IOI-HA. The psychometric properties of the questionnaire were shown to be strong and essentially the same for a sample of military veterans as for a private paying participant sample. There was a 95% chance that an observed change of one response unit between two test sessions reflected a true change in outcome. The study showed that the IOI-HA was a valid and reliable measure of global hearing aid outcomes.

In a within group study of 161 United Kingdom national health service patients aged 40 to 94 years (average age 72) Stephens (2002) showed that the IOI-HA was comprehensible to their patients and had weak correlation to demographics. This demonstrated the wide applicability of the IOI-HA. The IOI-HA was shown to consider how hearing aids help the participant's whole life regardless of what their specific problems might have been.

The combination of the initial screening criteria for the questionnaire (compatible with a retrospective study) and the evidence on the qualities of the IOI-HA questionnaire confirmed its selection for use in the present study.

1.9.4 Study design

1.9.4.1 Prospective or retrospective study

Ideally the present study would have had a prospective component in addition to a retrospective component. A prospective component of the study would have measured participant hearing aid outcomes after one or two months (that is also the typical hearing aid trial period) and related these outcomes to AVE measured just prior to hearing aid fitting. This would have shown the potential diagnostic value of the UCAMST to predict hearing aid candidacy. The reason for desiring such a prospective component to the present study was because hearing aid experience might change AVE scores or change their relationship to hearing aid outcomes. In addition, a prospective study could measure the outcome "hearing aid benefit" by comparing pre-fitting unaided hearing disability to aided hearing disability. Logistical constraints regarding access to potential participants who would be just about to be fitted with a hearing aid, limited the present study to enrolling only experienced hearing aid users (limited to a retrospective study).

1.9.4.2 Number of participants

The present study required 29 or more participants based on an a priori calculation. The calculation used an alpha-level of 0.05 and power of 0.80. The clinically meaningful effect size used was Cohen's d = 1.0 for the IOI-HA.

1.9.4.3 Minimum hearing aid usage experience

The study design determined the minimum period of time that a person needed to have used a hearing aid to be considered for enrolment in the present retrospective study. In a within group study of 134 participants aged 60 to 89 years with flat SNHI, Humes et al. (2002) found that hearing aid benefit measures were generally stable after one month's hearing aid use. From the day of first fitting until the end of the first month, benefit changed more rapidly with acclimatisation to the hearing aids. A more

conservative measure of the acclimatisation period allowed two months for benefit to stabilise. Self-reported benefit was shown to reduce at six months after initial hearing aid fitting, relative to the benefit reported one month after fitting. Based on this evidence, the present study only enrolled participants who had at least six months hearing aid usage experience.

1.9.4.4 Percent words correct used to measure auditory-visual enhancement

AVE was measured in a way that maximised the expected enhancement. As previously mentioned, Ma et al. (2009) and Picou, Ricketts and Hornsby (2013) showed that a SNR that results in participants achieving 15% of words correct in the auditory-alone condition produced the maximum AVE. The present study used the SNR for 20% of words correct (SNR_20%) rather than 15% correct. This is because 20% correct is one word correct in a matrix sentence of five words and is the percent correct offered by the UCAMST. For completeness, the present study also measured AVE at a SNR that results in participants achieving 80% of words correct (SNR_80%) in the auditory-alone. The measure at 80% correct is a feature provided by the UCAMST and also allows for analysis of the steepness of the performance function.

1.9.4.5 Loudness level for auditory tests

The present study used loudness scaling to ensure that speech was audible to participants so that test results showed SNR performance rather than audibility threshold performance. The QuickSIN test also uses a loudness scaling procedure for this purpose that procedure results in a sound level that maximises speech intelligibility. The present study designed a loudness scaling procedure intended to achieve the same goals as the QuickSIN procedure. The sound level resulting from this procedure in the present study was called the “recommended sound level”.

Several factors, as follows, influenced the design of the procedure used by the present study to select a loudness level for the testing of each participant.

The definition of hearing PTA used by the present study was the mean of the participant's 1 kHz and 4 kHz pure tone threshold (NZAS, 2007). This definition was used by practising audiologists throughout New Zealand and had the advantage that it was deterministic and did not require clinical judgement regarding the shape of the pure tone audiogram.

The present study used the concept of the “loud but OK” speech level used by the QuickSIN test and as described by Valente and VanVliet (1997). The scaling procedure in the present study used speech and noise samples rather than pure tones to find the “loud but OK” speech level. The reason for this was to allow the procedure to be applied from the UCAMST laptop computer without requiring an audiometer to also be available for pure tone presentation. In addition, much of the Valente and VanVliet (1997) study focussed on performing loudness scaling at multiple frequencies to assist in multi-frequency hearing aid adjustment for hearing aid fitting. The UCAMST did not allow frequency specific adjustment of speech sound level but instead used one overall loudness level setting. Instead of following the frequency specific loudness scaling procedure described in Valente and VanVliet (1997), an alternate procedure was designed to find the “loud but OK” speech level for each participant. The procedure was designed to be compatible with UCAMST features (see section 1.7.4.1) and to test each participant at a similar auditory sensation level.

The auditory sensation level is the difference between the presented sound level and the hearing threshold of a person (Katz et al., 2009). Speech is made of sound at many frequencies and a person's hearing impairment varies by frequency. For all participants in the present study to hear speech at a similar “loud but OK” sensation level, a mechanism that took into account the nature of speech and each participant's hearing impairment was required. The mechanism chosen by the present study was to use amplification gain targets produced by hearing aid prescriptions to recommend the sound level. National Acoustics Laboratory – Non-Linear version 2 (NAL-NL2) was selected as the prescription to

calculate amplification targets (Dillon, 2012). The NAL-NL2 prescription's approach is to calculate amplification targets that maximise speech intelligibility based on a person's pure tone audiogram (Dillon, 2012). The NAL-NL2 prescription approach does not result in amplification that produces the same sensation level at all frequencies for all degrees and shapes of hearing impairment. However, the goal of amplification in a hearing aid or in the auditory tests of the present study is to present sound at a level that maximises intelligibility. The approach of using the NAL-NL2 prescription results in an effectively equal speech intelligibility sensation level for all participants in the present study. This effectively equal sensation level used by the present study was limited by the normal speech spectrum presented by the UCAMST. The NAL-NL2 prescription in a hearing aid can amplify sounds by different amounts at different frequencies resulting in a speech spectrum that is ideal for speech intelligibility for each person. The present study used a mean of NAL-NL2 amplification targets for the UCAMST.

The QuickSIN test recommends a “loud but OK” sound level of 70 dB for SNR testing of persons without hearing impairment (Etymotic Research, 2006). This is similar to the 65 dB sound level used by the Audioscan Verifit1 Real Ear Measurement clinical test instrument (Audioscan, 2015) for medium level conversational speech. The present study used the Verifit1 instrument to estimate the “loud but OK” sound level for each participant using its medium level (65 dB) conversational speech hearing aid fitting verification algorithm. Each participant's audiogram was entered into the Verift1. The NAL-NL2 prescription was used to generate amplification targets. The mean of the amplification targets for 1 kHz and 4 kHz (the PTA frequencies) was added to 65 dB to produce the recommended sound level setting required in each ear for the UCAMST.

The recommended sound level setting was used as a starting point for loudness scaling to find the “loud but OK” sound level using the UCAMST features and the procedure described in section

1.7.4.1. The approach of using a sound level recommended by a prescription as a starting point that is then followed by subjective participant preference based adjustments (also called fine-tuning), is the same as the approach that should have been used when the participant hearing aids were fitted (Dillon, 2012 ; NZAS, 2013). This use of the same approach to set the sound loudness level should maximise the similarity between real-world aided listening sound levels and the sound levels while testing with the UCAMST.

In summary, the use of the Verifit1 with the NAL-NL2 prescription was intended to result in the recommended sound level setting meeting several desirable objectives:

- Being a “loud but OK” sound level,
- Being presented at an auditory sensation level that was similar to that experienced by a normal hearing person listening to speech at a 65 dB level (A level of 65 dB for a normal hearing person is similar to the 70 dB “loud but OK” level used by the QuickSIN test that maximises speech intelligibility),
- The auditory sensation level experienced by person's with different degrees of hearing impairment should be similar,
- The auditory sensation level should be similar to that experienced when using hearing aids. This increases the similarity between the conditions when AVE is used in the real-world wearing hearing aids, and when AVE is measured with the UCAMST unaided.

1.10 Statement of the problem

The main purpose of the present study is to use the University of Canterbury's new auditory-visual matrix sentence test tool (UCAMST) in a clinical setting to examine whether people with better AVI ability in background noise have better hearing aid outcomes. Additional purposes for the present study relate to the evaluation of the UCAMST.

Given the lack of direction from published studies, the present study's hypothesis is non-directional with regards to the relationship between AVE and hearing aid outcomes.

1.10.1 Research question

The research question for the present study is: Is auditory-visual integration ability in older adults related to hearing aid outcomes?

1.10.2 Hypothesis

The null hypothesis of the present study is: Better auditory-visual enhancement in noise is not related to self-reported hearing aid outcomes.

The hypothesis of the present study is: Better auditory-visual enhancement in noise is related to self-reported hearing aid outcomes.

2 CHAPTER TWO: Methods

2.1 Introduction

The purpose of this thesis was to begin the study of the relationship between the ability of older adults to integrate visual information and hearing aid outcomes. The ability to integrate visual information was measured using the UCAMST. Hearing aid outcomes were measured using self-assessed questionnaires. The study was limited to retrospective measurements of experienced hearing aid users and hence is a post-treatment study. This chapter discusses participant recruitment, test equipment, test procedure, and storage of results.

This study received ethical approval from the University of Canterbury Human Ethics Committee, New Zealand on 8 July 2016 (appendix 3). The procedures conducted in this study were in accordance with the committee's approval.

2.2 Participants

2.2.1 Database search

University of Canterbury Human Ethics Committee rules allow researchers to search the UCSHC client database because of the pre-approval for research that is part of client enrolment at the UCSHC. Candidate participants were be found by searching the client database for clients whose age was greater than 59. The resulting list of approximately 700 clients was exported to a spreadsheet including all data items from the database. The clients formed rows in the spreadsheet and the data items formed columns. The data items that formed the columns included: address, phone numbers, date of birth, hearing aid model, fitting date, and UCSHC administrative data.

Columns that were not of interest to the present study were deleted. The columns showing hearing aid fittings were manually analysed to find clients fitted with two hearing aids. All clients who had no hearing aids fitted or had a unilateral fitting were deleted from the spreadsheet. The data were manually analysed to find clients who had been fitted with hearing aids for at least six months before the date when participant testing was scheduled to begin. All clients who had less than six months experience were excluded, leaving 141 candidate participants, which were then screened based on pure tone audiometric threshold criteria. These criteria were:

1. At 250, 500, and 1000 Hz, mean better than 46 dB HL,

2. At 2000 Hz, worse than 34 dB HL and worse than the “250, 500, and 1000 Hz mean”,

3. At 4000 and 8000 Hz, mean worse than 40 dB HL and worse than the “250, 500, and 1000 Hz mean”,

4. At 2000 and 4000 Hz, no air-bone gap of more than 15 dB .

As explained in sections 1.5 and 1.6, participants with a downward sloping hearing impairment were sought. The above audiometric threshold criteria were derived from Erber's Area (Erber, 2002) and to ensure that the criteria were not so strict that too few candidate participants met the criteria. After ensuring candidate participants met the audiometric criteria and ensuring they had indicated a willingness to be contacted for research, the list of participants became the pool to be invited for inclusion in the study. There were 48 candidate participants eligible to be sent an invitation letter. All 48 candidates were mailed an invitation letter.

2.2.2 Invitation letters

The candidate participant invitation envelopes were prepared by the researcher (the researcher was also the author of the present study) and contained the following information:

1. Study flyer: this is a study summary in advertisement format (appendix 1.1),

2. Letter of Interest: this is a form (appendix 1.2) for the participant to confirm interest in participating in the study and to provide further contact information. An additional formal consent form (appendix1.4) was provided at the face-to-face meeting testing appointment,

3. Study Information Sheet: this explained details about the study (appendix 1.3),

4. Return postage paid envelope addressed to the University of Canterbury research supervisor.

2.2.3 Participant expression of interest

Candidate participants expressed interest in participating in the study by either returning the letter of interest in the provided postage paid envelope or by telephoning the research supervisor. Candidate participants provided up to date contact details that the researcher recorded in the spreadsheet.

The researcher telephoned the candidate participants who had returned the letter of interest or had contacted the research supervisor by phone or email. During the telephone discussion the researcher provided further explanation about the research study and what participants would be expected to do.

Of the 48 candidate participants invited to participate, 16 returned letters of interest or contacted the research supervisor. All 16 were telephoned by the researcher and volunteered. Of the 16 who volunteered, four withdrew before their testing appointment due to deteriorating health or other commitments. Therefore, a total of 12 participants attended testing appointments.

2.3 Test equipment

Participant test appointments were held at the UCSHC. Testing using the UCAMST was conducted in a quiet room. The QuickSIN test was administered in an audiology sound booth using an audiometer with attached compact disc (CD) player.

The UCAMST software was run on a laptop computer. The UCAMST software can be run on almost any computer. The important hardware for the UCAMST is the USB connected external sound card and the headphones connected to the sound card. The specifications for these were as follows.

- External sound card: Sound Blaster X-Fi Surround 5.1 Pro (Creative Labs, Singapore),
- Pair of headphones: Sennheiser HD 280 Pro headphones (Sennheiser electronic GmbH & Co. KG, Germany).

2.4 Test procedure

2.4.1 Test appointment preparation

A test results sheet, as shown in appendix 2.1, was prepared for each participant. Participants were met at the UCSHC reception and then the test procedure began in a UCSHC audiology research room. The participant was reminded of the study purpose and what they would be expected to do over the following two hours. The participant was then given the option to withdraw from the study or sign a consent form. The discussion around the consent form was also used as the means of assessing whether the participant was a native English speaker and this was recorded on the participant's test sheet.

The final step before testing began was to use an otoscope to examine the participant's right and left ear canals for occluding wax. The wax status was recorded on the participant's test sheet. The purpose

of the check for occluding wax was to find wax that would block sound and interfere with tests that present sound. No participants had sufficient wax to require a request to the participant to have the wax removed and the test appointment rescheduled.

2.4.2 Eye test

The first test for each participant was the Snellen Eye Chart test (Hetherington, 1954). A commercially available professional Snellen Eye Chart was used. The eye chart was illuminated by both the room light and a 700 lumen warm white LED mirror reflector down light fitted into a desk lamp and pointed towards the eye chart. When the eye chart had been first placed on the wall, there had been a biological calibration of the lighting level using the research's own vision. The researcher had previously been tested at an optometrist's clinic and was found to have 20/20 feet vision (also called 6/6 metre vision). The researcher was able to read the 20/20 feet line on the Snellen Eye Chart in the UCSHC audiology room which confirmed illumination calibration for research participant testing.

The participant was asked to wear their eye glasses only if they normally wore them while talking to people. The participant stood in a corridor at a mark 20 feet from the eye chart and was asked to read each row of the Snellen Eye Chart from left to right starting at the top until they could not read the letters any more. Guessing was encouraged. Once the participant made any errors in a row, they were asked to repeat the row to rule out accidental errors. Once the row with the smallest letters the participant could get all correct was identified, the visual acuity level associated with that row was written on the results sheet. The visual acuity was recorded as one of 20, 25, 30, 40, 60, or “worse” feet.

2.4.3 UCAMST

After the eye test, the participant was asked to sit in front of the UCAMST. The participant was given a piece of paper showing instructions (appendix 2.2) for the tests. The researcher then discussed the instructions with the participant. The UCAMST was set up with a participant display screen visible to both the participant and the researcher and a laptop screen visible only to the researcher. The UCAMST software ran on this laptop. A piece of string 1.1 metres long was used to adjust the participant's seat position so that the participant's face was 1.1 metres from the display screen. The participant's hearing aids were removed for the duration of the UCAMST testing.

Once the participant was comfortable and ready for UCAMST testing, the researcher ran the UCAMST application on the laptop. The test options were set for the auditory-alone test. The loudness level was set to the recommended levels for the right and left ears using the values previously obtained from the NAL-NL2 prescription on the Verifit1. The participant was asked to repeat the words they heard through the headphones and think about whether the sound level was audible or uncomfortably loud. The loudness scaling procedure then began. A randomly generated matrix sentence speech sample was presented to the right ear. The participant was asked if the sentence was audible or too loud. This procedure was repeated for the left ear. If needed, the sound level was adjusted down to a level tolerable to the participant. Next the sound level for the right and left ears was lowered by 15 dB and sample matrix sentences were presented to the right and left ears. The participant was asked if they could easily understand (clearly audible in the absence of masking noise) this 15 dB lower sound level. If necessary, the sound level setting was raised to make the 15 dB lower level audible. The goal was to find the sound level setting that was tolerable while the 15 dB lower level was clearly audible. Once this was found, two more practice matrix sentences were presented and repeated by the participant at the sound level setting. At this point, the participant had

heard between six and eight matrix sentence speech samples. The loudness scaling procedure also provided the participant with an opportunity to practice repeating matrix sentences before scored testing began. Before beginning the automated auditory-alone test, the masking noise that is always presented at the speech sound level setting was demonstrated in both ears. The final step was to provide instructions regarding listening to speech-in-noise and guessing the words heard when uncertain.

The researcher started the auditory-alone automated test. After each matrix sentence was presented to the participant, the participant repeated back what they thought they heard. The researcher's laptop screen displayed the correct answers and the researcher scored the words that had been correctly repeated by the participant. The test software presented matrix sentences at different SNRs that were achieved by varying the speech sound level but with the noise level at the selected constant level. The sound would automatically adjust to a variety of levels to find the levels that best fit the participant achieving 20% of words correct and 80% correct. This is called a dual track adaptive procedure in the UCAMST. After 15 sentences were presented, the test ended and results were displayed on the laptop screen. The researcher wrote onto the test results sheet the values for both SNR_20% and SNR_80%.

Following the auditory-alone test, the researcher selected the test options to prepare for the auditory-visual test. The researcher instructed the participant to watch the lips of the person talking on the computer screen at the same time as listening to the person using the headphones. Guessing was again encouraged. The researcher started the test of 15 new matrix sentences. The UCAMST automatically used the sound levels from the auditory-alone test for SNR_20% and SNR_80% to measure the participant's percent correct with visual information at these two sound levels. The sound level alternated pseudo-randomly between the louder and quieter levels for the 15 sentences so that the participant did not have too many difficult to hear sentences at the quieter level in a row. After each

matrix sentence was presented to the participant, the participant repeated back what they thought the speaker said. The researcher's laptop screen displayed the correct answers and the researcher scored the words that had been correctly repeated by the participant. After 15 sentences were presented, the test ended and results were displayed on the laptop screen. The researcher recorded the percent correct achieved by the participant at the SNR_20% and SNR_80% sound levels. As described in section 1.2.2.1, the AVE percentage achieved by the participant was calculated using the following formula:

AVE percentage = ((AV – A) / (1 – A)) * 100

The final test using the UCAMST was the visual-alone test. The researcher selected the test options to prepare for the visual-alone test. The researcher instructed the participant to watch the lips of the person talking visible on the computer screen. Guessing was again encouraged. The researcher boosted the confidence of the participant by explaining that lipreading without sound is not easy but the participant should expect to be surprised by how many words they actually got correct. The researcher started the test of 15 new matrix sentences. After each matrix sentence was visually presented to the participant, the participant repeated back the words they thought they saw. The researcher's laptop screen displayed the correct answers and the researcher scored the words that had been correctly said by the participant. After 15 sentences were presented, the test ended and results were displayed on the laptop screen. The percent correct achieved by the participant was recorded by the researcher.

2.4.4 IOI-HA Questionnaire

Following the set of tests using the UCAMST, the participant put their hearing aids back on before filling in the IOI-HA questionnaire. The IOI-HA questionnaire had eight questions with each question having a five-item response format. The researcher read out loud the first question while the

participant was also able to read the question. When necessary, the researcher provided clarifying commentary on the meaning of the question. The participant selected the item from the five possible responses that best fit their experience with their hearing aids. This process was repeated for all eight questions on the IOI-HA questionnaire.

2.4.5 Reading span test

Following the administration of the IOI-HA questionnaire, the researcher administered the RST to the participant. The participant was given a piece of paper showing instructions (appendix 2.3) for the RST. The researcher discussed these instructions with the participant. The researcher sat to the immediate left of the participant at a desk. The research had a score sheet with the correct answers being hidden under a fold of paper. The sentences for the RST were printed on small paper cards. Each card had a hole at the left end and a piece of string went through the set of cards to keep them in the correct order. A participant's Reading Span is defined as the number of sentences (cards) that a participant can read out loud and still remember the last word on all of the cards.

The test procedure started with practice cards at the two-sentence level. This was followed by a real test at the two-sentence level, then the three-sentence level, and so on until the participant was unable to remember the last word of sentences. At each reading span difficulty levels, the participant was given three sets of cards and was scored at the end of each of the three sets. To pass a reading span difficulty level, the participant must have been 100% correct for at least two of the three card sets. The test procedure ended when the participant did not achieve 100% correct for any of the three card sets at a particular difficulty level.

The researcher started testing a participant by making the first practice card visible to participant. The researcher instructed the participant to read the sentence on the card out loud and to stress the last

word of the sentence to help to remember it. The researcher then turned to the next card and asked the participant to read it out loud. The researcher then turned to the next card, which was a blank card. The researcher then asked the participant to say out loud the last word of each of the previous sentences on the two cards. The researcher wrote down the participant's answers on the score sheet. The researcher instructed the participant to, in future, use blanks cards as the trigger to say the last words of the previous card sentences out loud. The above procedure was repeated for the next two practice sets with each set having two cards. Following the three practice sets of two cards, the researcher presented the real test of three sets of two cards, followed by three sets of three cards, three sets of fours cards, and so on.

At the end of a participant's RST, the researcher wrote down the reading span achieved (longest span with two or more of the three sets of cards correct) and the test end difficulty level (span size with all three sets of cards incorrect) on the test results sheet.

2.4.6 Study questionnaire

Following the RST, the participant was given the study specific questionnaire (appendix 2.4) to fill in. The study specific questionnaire had six questions. The researcher read out loud the first question while the participant was also able to read the question. When necessary, the researcher provided clarifying commentary on the meaning of the question. The participant wrote down their answer. This process was repeated for all six questions of the study specific questionnaire.

2.4.7 Montreal Cognitive Assessment

Following the study specific questionnaire, the researcher administered the MoCA to the participant. The researcher began by explaining that the purpose of the test was to assess cognitive skills that might have an affected on their ability to listen to speech-in-noise. The researcher put the participant

at ease with regards to the context of a test that participants might fear as a dementia test. The researcher explained to the participant that the MoCA is much more difficult than a dementia test because it is looking for mild cognitive impairment. The researcher held a copy of the MoCA instructions and, while sitting next to the participant, put the MoCA questionnaire on the desk in front of the participant. The MoCA questionnaire was folded such that the sections below the pictures of animals (below the first two rows) could not be seen by the participant. The researcher led the participant through the first two rows of the MoCA that require the participant to see and write on the form. After the first two rows, the researcher held both the MoCA questionnaire and instructions behind a screen that the participant could not see through. Encouragement was given to the participant throughout the MoCA to keep the participant engaged and willing to continue trying their hardest, even after finding some tests quite difficult. Once the end of the MoCA questionnaire was reached, the researcher totalled the score. This was the MoCA raw score. The researcher then asked the participant when they left school and if they had undertaken tertiary education. As explained in the MoCA instructions, if the participant had not gone through tertiary eduction, then one point was added to their MoCA raw score. This was the MoCA adjusted score. The researcher wrote down the MoCA raw and adjusted scores on the test results sheet.

A MoCA adjusted score of less than 26 is considered abnormal. When a participant scored less than 26, they were offered the letter “Re: Cognitive screening assessment as part of the research project” shown in appendix 2.5. The participant was offered this letter to present to their doctor. Before being given this letter, the participant was given counselling regarding the MoCA and what an abnormal score meant. It was explained that an abnormal MoCA score does necessarily mean that the participant has a serious problem. The MoCA is a screening test that detects if a person might have some problems with thinking and memory. The participant was then shown the letter and given the opportunity to read it and ask questions. The researcher then asked the participant if they wanted the

letter to give to their doctor or for their own records. Some participants took the letter and some did not. Whether the letter was given out or not was recorded on the test results sheet.

2.4.8 QuickSIN test

The final test for each participant's testing appointment was the QuickSIN. The manual for the QuickSIN test had previously been downloaded (Etymotic Research, 2006). The participant was taken from the research room to the sound booth. The QuickSIN test procedure was explained to the participant with their hearing aids in and then the hearing aids were removed in preparation for the test. The participant sat on a chair in the sound booth and was given the standard instructions recommended in the QuickSIN manual. Headphones were put over the participant's ears and the sound booth door was closed. The researcher set up the audiometer to play sound into both of the participant's ears. The starting sound level selected was the level previously written on the test results sheet during UCAMST loudness scaling. The researcher spoke to the participant through the headphones using the audiometer microphone. The participant was asked to think about whether the sound level they were about to hear was uncomfortably loud, loud but OK, or could be made louder. The researcher presented the first sentence of the first QuickSIN test practice list to the participant. The participant repeated the sentence they thought they had heard among the multi-talker babble noise. The researcher informally marked the response (practice responses were not part of the QuickSIN test result) and then asked the participant about the sound level. If necessary, the sound level was adjusted before the next practice sentence was presented. By the end of the practice sentence list, a “loud but OK” sound level had been confirmed for use with the subsequent scored sentence lists.

Once the QuickSIN test practice sentence list presentation had been completed, the researcher presented two tests lists. The lists were scored and the two results were written onto the test results

sheet. The mean result was calculated and written onto the test results sheet. The result of the QuickSIN test was shown to the participant and discussed while the participant was shown Table 1 of the QuickSIN manual.

2.4.9 Test appointment completion

Once the QuickSIN test results had been explained, the participant was informed that testing had come to an end. The participant was given an opportunity to ask any final questions. The researcher offered the participant a $NZ 20 petrol voucher to reimburse the expense of travelling to the UCSHC. The participant number and voucher number was recorded on an accounting sheet. The participant signed for the received voucher and then left the UCSHC.

The final step of the participant testing appointment involved the researcher going to the UCSHC's file room to collect additional information from the participant's paper file. The test results sheet shown in appendix 2.1 had a form on the last page to collect this information. The information included the participant's audiogram, hearing aid information, and information about their hearing aid fitting.

2.5 Results storage

Materials resulting from the participant testing appointment were stored in one envelope for each participant. The participant consent forms were photocopied and the copies kept in the participant envelopes. The original consent forms were put into another envelope and were stored in the thesis supervisor's office. The participant envelopes were also stored in the supervisor's office.

The participant data resulting from the testing appointments were entered into a results spreadsheet in preparation for data analysis using the software package “IBM SPSS” version 23. Further details about these data are presented in the Results chapter.

3 CHAPTER THREE: Results

3.1 Introduction

The purpose of this thesis was to begin the study of the relationship between the ability of older adults to integrate visual information and hearing aid outcomes. The ability to integrate visual information was measured using the UCAMST. Hearing aid outcomes were measured using self-assessed questionnaires. This chapter presents measured data and the analyses performed on the data to show if the study hypotheses were supported by the data.

Data analysis was performed using SPSS version 23 software.

3.2 Participants

Thirteen participants were tested at the UCSHC. Twelve of these participants went through the candidate participant invitation process described in sections 2.2.2 and 2.2.3. One of the thirteen tested participants was not recruited using the invitation process, but was a friend of another participant and volunteered by contacting the researcher. This participant's test results were excluded from the study, because his audiometric air-bone gap was too large to meet the inclusion criteria used to invite other participants. Another participant's test results were determined to be an outlier (see the box plot analysis below) with unusual characteristics suggesting a technical or procedural error in testing. The outlier's data was excluded from all group data analysis, including being excluded from the description of participants.

Eleven participants' data are reported and analysed. There were two male participants and nine females. The mean participant age was 77.9 years. The youngest was aged 65 years and the oldest 86 years. All participants self-reported that they were of European decent. All participants spoke

excellent English (assessed by the researcher) and all but one were native English speakers. One participant spoke another European language from birth but had been in New Zealand for several decades as an adult. The mean participant visual acuity was 36.8/20 feet. The best visual acuity was 25/20 feet and the worst was 60/20 feet.

The mean participant right ear 1 kHz and 4 kHz PTA was 47.0 dB and the left was 49.8 dB. Both of these means represented “moderate hearing impairment” (NZAS, 2007). Figure 4 below shows an audiogram for the mean audiometric threshold of the group of participants. The mean right ear hearing threshold at 250 Hz was 23.7 dB HL and was 71.8 dB HL at 8000 Hz. Mean left ear thresholds were similar to right ear thresholds. The mean hearing threshold was worse for each octave as the frequency increased, consistent with a sloping high frequency hearing impairment.

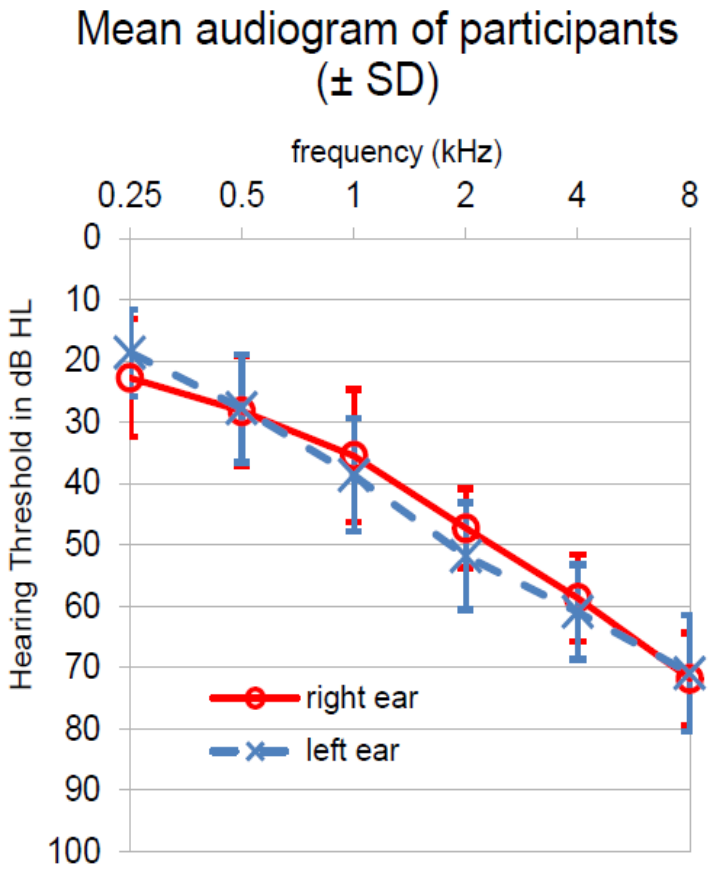

Figure 4. **Mean audiogram of participants**

3.3 Results tables

Table 2 shows the results obtained from the UCAMST. AVE was the predictor variable for this study. It was hypothesised that this predictor variable was related to participant hearing aid outcomes.

Variable	Units	Mean ± SD	Minimum	Maximum
SNR_20%	dB SNR	-4.2 ± 1.6	-6.8	-1.5
Auditory-visual score at SNR_20%	Percent	64.8 ± 11.4	41.3	82.7
Normalised AVE at SNR_20%	Percent	56.0 ± 14.2	26.7	78.0
SNR_80%	dB SNR	6.4 ± 4.0	1.0	14.7
Auditory-visual score at SNR_80%	Percent	90.4 ± 4.8	80.0	96.0
Normalised AVE at SNR_80%	Percent	52.0 ± 24.1	0.0	80.0
Visual-alone percent correct	Percent	24.5 ± 10.0	8.0	44.7

Table 2. **Predictor variables**

Table 3 shows the results obtained from participant answers to the IOI-HA questionnaire. The IOI-HA results were the present study's primary means of measuring hearing aid outcomes and was the study outcome variable. It was hypothesised that this outcome variable was related to the AVE predictor variable. In addition to results for the questions in the IOI-HA questionnaire, there is an additional calculated outcome that is the mean of the results from the questions (IOI-HA-Average). This ability to use all the outcomes together was called the “global score” in the study by Smith, Noe and Alexander (2009).

Variable	Units	Mean ± SD	Minimum	Maximum
IOI-HA-Q1: USE	Selection from 1 to 5	4.1 ± 0.9	3.0	5.0
IOI-HA-Q2: Ben	Selection from 1 to 5	4.0 ± 0.6	3.0	5.0
IOI-HA-Q3: RAL	Selection from 1 to 5	3.5 ± 0.9	2.0	5.0
IOI-HA-Q4: Sat	Selection from 1 to 5	4.1 ± 0.8	3.0	5.0
IOI-HA-Q5: RPR	Selection from 1 to 5	4.1 ± 0.8	3.0	5.0
IOI-HA-Q6: Ioth	Selection from 1 to 5	3.8 ± 0.9	2.0	5.0
IOI-HA-Q7: QoL	Selection from 1 to 5	3.9 ± 0.8	3.0	5.0
IOI-HA-Average	Selection from 1 to 5	3.9 ± 0.6	3.1	4.7
IOI-HA-Q8: Unaided difficulty	Selection from 1 to 5	2.6 ± 0.5	2.0	3.0

***Table 3*. IOI-HA outcome variables**

The results for question 8 of the IOI-HA questionnaire were not analysed as an outcome for the present study. Question 8 is not a hearing aid outcome but is about unaided hearing difficulty. Depending upon the answer to question 8, different sets of normative data should be used with the IOI-HA. This normative data allows the determination of whether IOI-HA results for questions 1 to 7 were within normative ranges for an individual participant or a group of participants. The group of participants in the present study had responses to question 8 that varied from 2 to 3 and hence no

single set of normative data could be used for the participant group in the present study. Instead, two sets of normative data were used.

Table 4 shows participant group mean responses to IOI-HA questions 1 to 7 in comparison with two sets of normative data published by Cox et al. (2003) depending upon the responses to question 8. The results from the present study in Table 4 are shown in two columns. One column shows results for all participants who answered "2" to question 8 (moderately severe unaided hearing difficulty) and one column for all participants who answered "3" (moderate unaided hearing difficulty) to question 8.

IOI-HA question	**Norm for Q8=2 (mean ± SD)**	**Present study result for Q8=2**	**Norm for Q8=3 (mean ± SD)**	**Present study result for Q8=3**
Q1	4.5 ± 0.96	3.75	3.73 ± 1.17	4.29
Q2	3.52 ± 1.08	4.00	3.39 ± 0.98	4.00
Q3	3.19 ± 1.05	3.00	3.4 ± 0.95	3.71
Q4	3.84 ± 1.17	4.00	3.2 ± 1.21	4.14
Q5	3.38 ± 1.11	4.00	3.57 ± 1.13	4.14
Q6	3.38 ± 1.1	3.75	3.79 ± 1.13	3.86
Q7	3.68 ± 1.02	3.75	3.19 ± 0.93	4.00

***Table 4*. IOI-HA results compared to published norms**

Table 5 shows the results obtained for other measured and calculated variables. Some of these variables were control covariates discussed in section 1.8. An example of such a control covariate is the "MoCA adjusted score". Additional variables where measured or calculated as part of the process of performing other tests. Any relationship between these variables and the study predictor and outcome variables may be of interest.

Variable	Units	Mean ± SD	Minimum	Maximum
Age of participants	Years	77.9 ± 5.4	65.0	86.0
Visual acuity of participant	Feet at 20 feet distance (normal = 20)	36.8 ± 15.0	25.0	60.0
Right loudness NAL-NL2 suggested	dB HL	82.6 ± 3.0	78.0	85.0
Left loudness NAL-NL2 suggested	dB HL	84.8 ± 3.8	80.0	90.0
Right loudness used	dB HL	83.6 ± 4.5	75.0	90.0
Left loudness used	dB HL	85.0 ± 5.5	70.0	90.0
Reading span with three sets wrong	Number of cards	3.2 ± 0.4	3.0	4.0
Reading span with two or more sets correct	Number of cards	1.9 ± 0.7	0.0	3.0
Daily hours of hearing aid use	Hours	7.9 ± 4.3	2.0	14.0
Hearing impairment onset age	Years	60.6 ± 18.9	20.0	84.0
MoCA raw score	Points	24.7 ± 2.6	21.0	28.0
MoCA adjusted score	Points	25.5 ± 2.6	22.0	29.0

	(normal ≥ 26)			
QuickSIN SNR loss	dB (normal = 0)	10.3 ± 3.8	5.0	18.0
QuickSIN loudness used	dB	83.6 ± 3.9	75.0	90.0

***Table 5*. Control covariates and other variables**

3.4 Data pre-analysis

Prior to analysing predictor and outcome variables for relationships between them, the data requires analysis to determine whether to use parametric or non-parametric data analysis and to look for outlier measurements (Field, 2013).

3.4.1 Parametric vs. non-parametric analysis

Parametric data analysis requires that the data being analysed meet some measures of normal distribution assumptions (such as the central limit theorem) whereas non-parametric data analysis does not require these assumptions.

The method of analysis selected for measuring any relationship between the study predictor and outcome variables was “correlation”. Correlations show the extent to which variation in one variable can be attributed to variation in another variable, and hence to what extent they are related (Field, 2013). There is a parametric correlation analysis named “Pearson” and a non-parametric correlation analysis named “Spearman”. Pearson parametric correlation analysis requires that some measures of normal distribution assumptions apply, including the central limit theorem. A sample of 11 participants is too small for the central limit theorem to apply and hence the non-parametric Spearman correlation analysis was used to look for relationships between predictor and outcome variables. A

sample of 30 or more participants (Field, 2013) would have allowed the use of the Pearson parametric correlation analysis.

3.4.2 Outlier analysis

Figure 5 and Figure 6 show box plots for the study's predictor variable and the global hearing aid outcome variable (IOI-HA-Average) for the 12 participants included in the study.

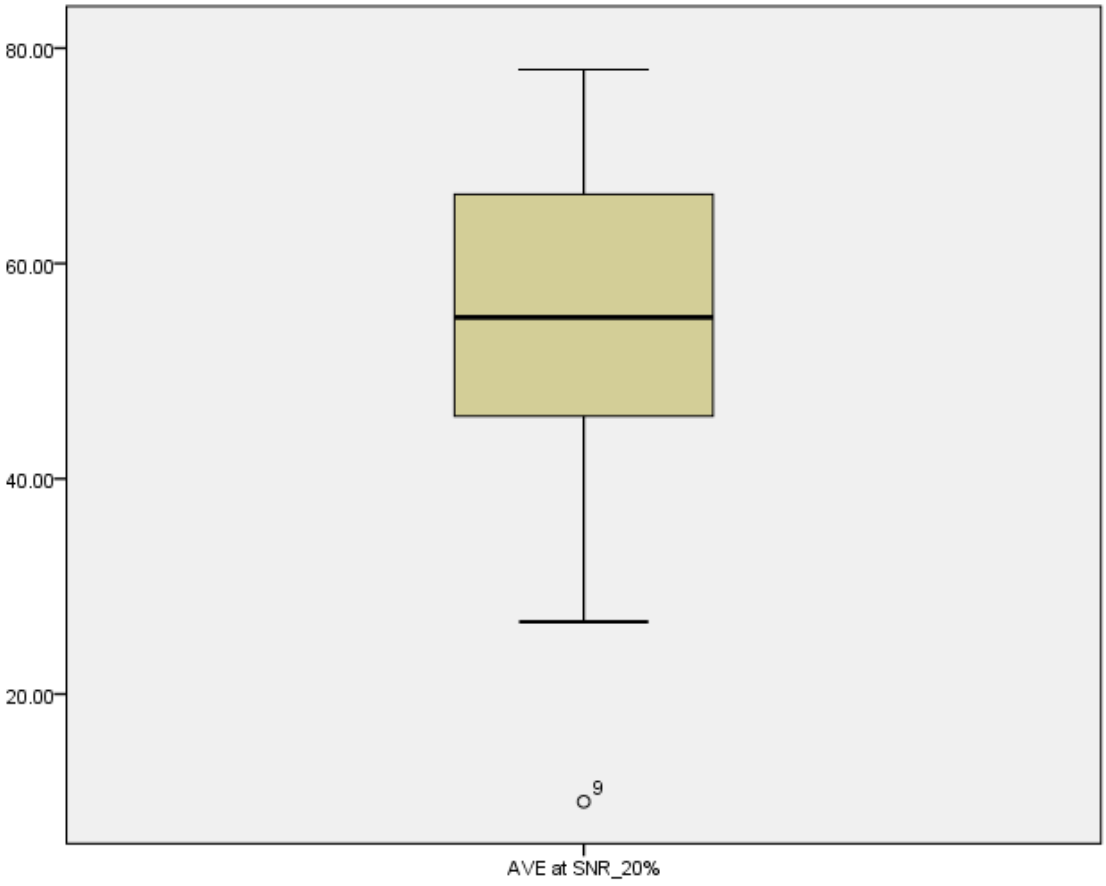

***Figure 5*. Non-trimmed box plot for AVE predictor variable at SNR_20%**

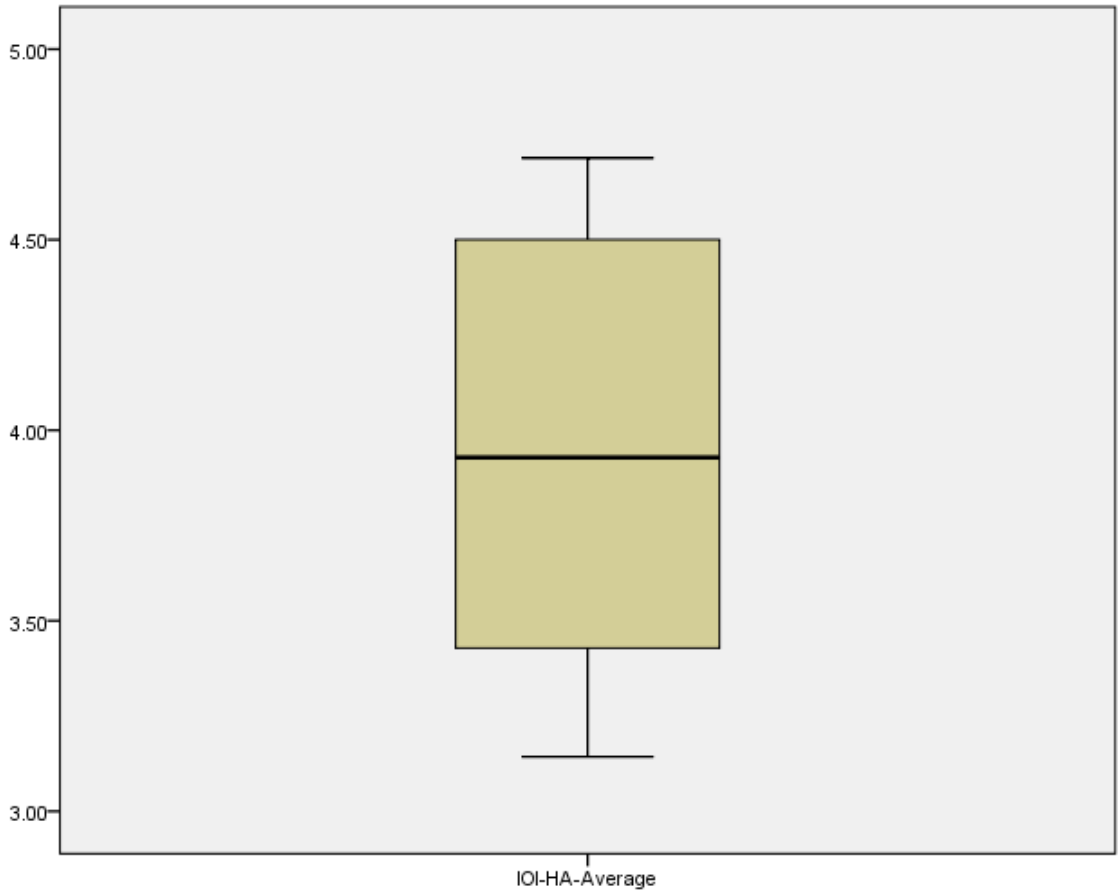

***Figure 6*. Non-trimmed box plot for IOI-HA-Average outcome variable**

The box plot for the predictor variable AVE_20% showed an outlier (O^9 in Figure 5). Analysis of data for the outlier participant showed unusual results for the SNRs that resulted in 20% correct and 80% correct. The unusual results suggested a technical or procedural error in testing for this participant. This outlier participant's data were deleted from the study prior to further analysis. Figure 7 and Figure 8 show box plots for the study's main predictor and outcome variables for the 11 remaining participants after outlier trimming.

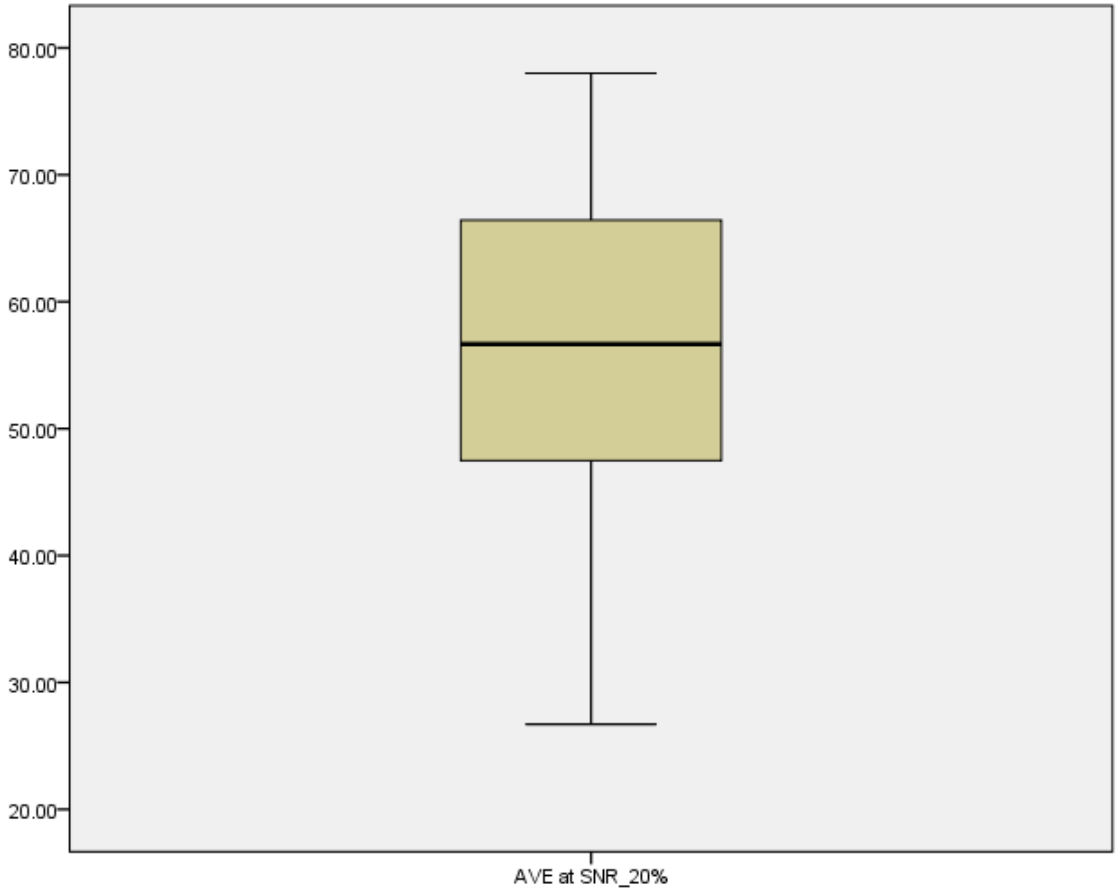

***Figure 7*. Trimmed box plot for AVE predictor variable at SNR_20%**

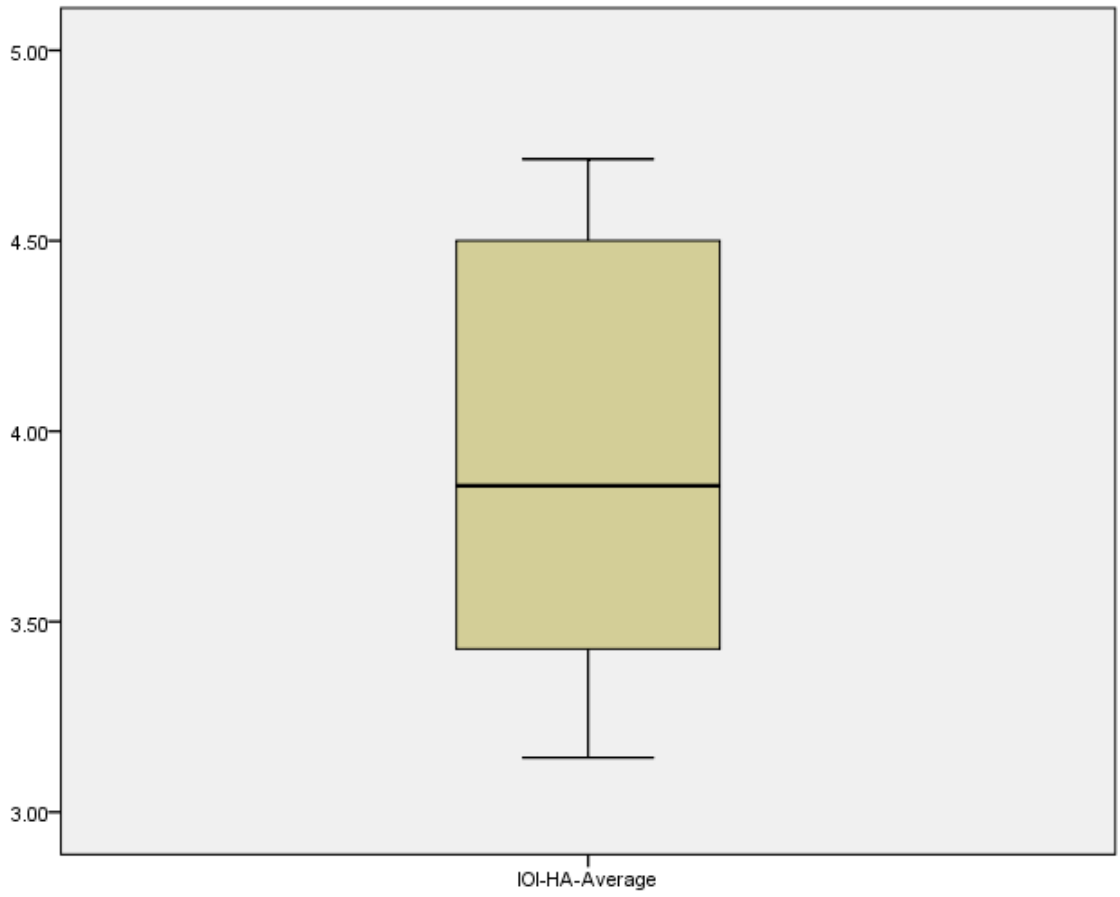

***Figure 8*. Trimmed box plot for IOI-HA-Average outcome variable**

The box plots generated after the removal of the single outlier showed no remaining outliers for the remaining 11 participants.

3.5 Data analysis

Correlation analysis of data was performed to show if there were relationships between predictor and outcome variables. The statistical significance of the correlation was also analysed. The criteria used to define a statistically significant relationship was $p < 0.05$. This criteria meant that there was a less than 5% chance that observed relationships in the sample group of study participants would not exist in the general population (population correlation of zero).

3.5.1 Correlation with covariates

Before measuring the correlation between predictor and outcome variables, the correlation with candidate control covariates was measured. This determined which of the candidate covariates should have been used as statistical controls when measuring the correlation of the predictor and outcome variables.

Controlling for the effect of covariates on outcome variables, estimates the variation in the outcome variable that is uniquely related to the contribution of predictor variables. Measuring the correlation of covariates with predictor variables estimates the extent that covariates may be related to outcome variables through their relationship to predictor variables. Table 6 and Table 7 show the Spearman correlation of covariates to the study outcome and predictor variables. Covariates were only correlated with the global hearing aid outcome (IOI-HA-Average). Gender was not used as a covariate because there were insufficient male participants available for analysis with only two of the 11 participants being male.

Covariate Name	MoCA Adjusted	Visual Acuity	Reading span with three sets wrong	Reading span with two or more sets correct	Visual-alone percent correct	Hearing impairment onset age
Correlation with IOI-HA-Average	0.044	0.471	-0.075	0.544	-0.034	0.227
Statistical significance	0.898	0.143	0.826	0.083	0.92	0.501

***Table 6*. Correlation of covariates to IOI-HA-Average outcome variable**

Results in Table 6 showed that none of the covariates of the outcome variable reached a statistically significant level of $p < 0.05$. The covariate “Reading span with two or more sets correct” is the closest

with a probability of 8.26% that the correlation comes from chance. However, it does not meet the $p < 0.05$ threshold of significance. Hence, this table provides no covariates to include in a partial correlation of the study predictor and outcome variables.

Covariate Name	MoCA Adjusted	Visual Acuity	Reading span with three sets wrong	Reading span with two or more sets correct	Visual-alone percent correct	Hearing impairment onset age
Correlation with AVE	-0.386	0.234	0.373	0.405	0.656	0.101
Statistical significance	0.241	0.489	0.259	0.217	0.028	0.767

***Table 7*. Correlation of covariates to AVE predictor variable**

Results in Table 7 showed that only one co-variate of the predictor variable AVE reached a statistically significant level of $p < 0.05$. That covariate is "visual-alone percent correct". As discussed in section 1.8.9, this covariate was not an extraneous variable from the study predictor variable AVE, and hence was not measured for the purpose of use in a partial correlation. In addition, this covariate is not significantly related to the study outcome variable and therefore could not replace the study predictor variable. Hence, this table provides no covariates to include in a partial correlation of the study predictor and outcome variables.

3.5.2 Predictor and outcome variable correlation

The study predictor and outcome variables were correlated using a Spearman non-parametric method, while including no partial correlation covariates. The results are shown in Table 8.

Outcome Variable Name	Daily hours of hearing aid use	IOI-HA-Average	IOI-HA-Q1 USE	IOI-HA-Q2 Ben	IOI-HA-Q3 RAL	IOI-HA-Q4 Sat	IOI-HA-Q5 RPR	IOI-HA-Q6 Ioth	IOI-HA-Q7 QoL
Correlation to AVE	0.161	0.440	0.211	0.429	0.343	0.380	0.496	0.130	0.429
Statistical significance	0.636	0.175	0.534	0.188	0.302	0.248	0.121	0.704	0.188

***Table 8*. Correlation of outcome variables to AVE predictor variable**

Results in Table 8 showed that none of the correlations between the study predictor variable and the outcome variables had a statistical significance of $p < 0.05$. The results in Table 8 are shown again in Table 9 but in rank order of correlation to AVE.

Hearing aid Outcome	**Correlation to AVE**	**Significance (p)**
IOI-HA-Q5 - Residual participation restrictions (RPR)	0.496	0.121
IOI-HA-Average	0.440	0.175
IOI-HA-Q2 - Benefit (Ben)	0.429	0.188
IOI-HA-Q7 - Quality of life (QoL)	0.429	0.188
IOI-HA-Q4 - Satisfaction (Sat)	0.380	0.248
IOI-HA-Q3 - Residual activity limitations (RAL	0.343	0.302
IOI-HA-Q1 - Hours of daily use (USE)	0.211	0.534
Daily hours of hearing aid use	0.161	0.636
IOI-HA-Q6 - Impact on others (Ioth)	0.130	0.704

***Table 9*. Outcome variables ranked by correlation to AVE predictor variable**

Figure 9 shows a scatter plot of the correlation between the study predictor variable AVE and the study global hearing aid outcome variable IOI-HA-Average.

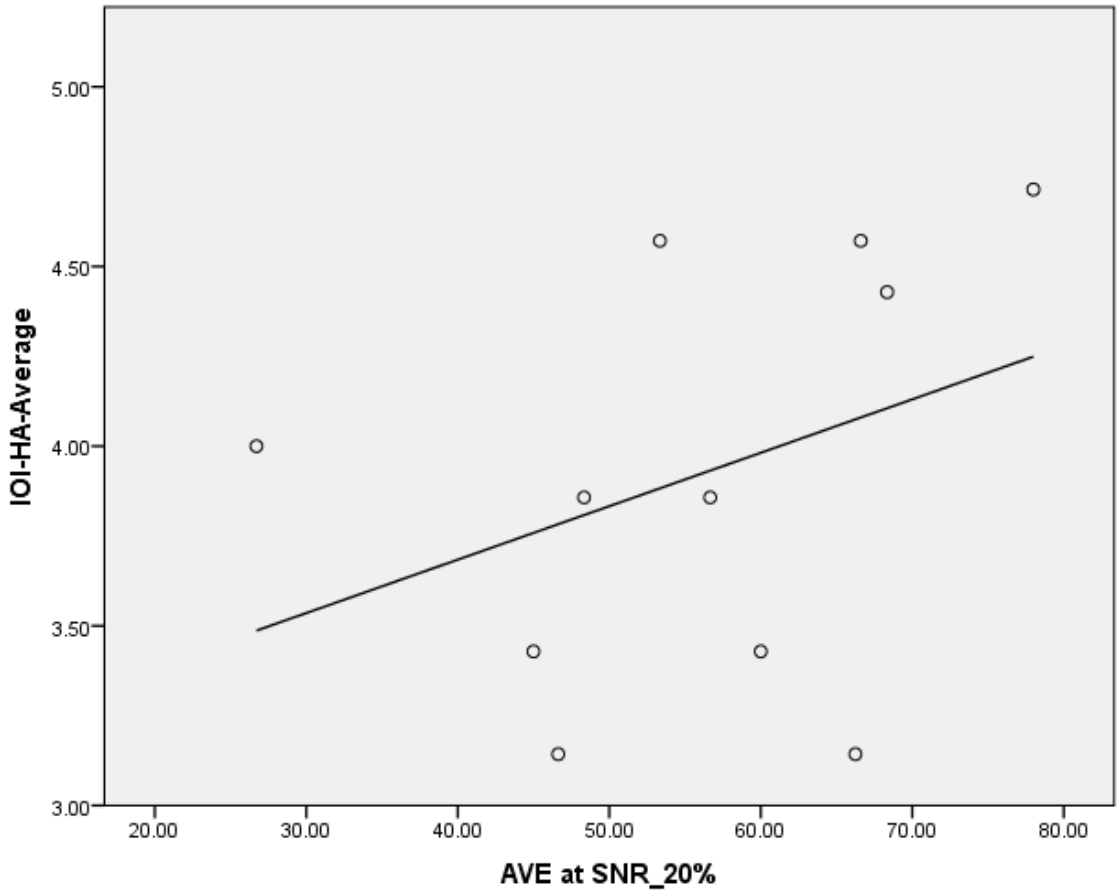

***Figure 9*. Scatter plot correlation of study predictor and outcome variables**

3.6 UCAMST compared to QuickSIN test

As explained in section 1.8.2, the present study measured participant performance for the QuickSIN test as a potential control covariate and also to compare results to the SNR loss measured by the UCAMST used in auditory-alone mode. If the results of the two test tools were similar then this suggests that, in addition to providing new auditory-visual test data, the UCAMST could also potentially remove the need for QuickSIN testing in clinic.

Table 10 shows the correlation of participant QuickSIN test scores with potential covariates from the present study. Results in Table 10 showed that the QuickSIN SNR loss results were not significantly related to the study predictor or outcome variables at the $p < 0.05$ level of statistical significance. The QuickSIN SNR loss results were significantly related to the UCAMST SNR_20% results, as shown in Table 10. For UCAMST SNR_80%, the analysis showed that p is just above the $p < 0.05$ statistical significance threshold, as shown in Table 10. Figure 10 and Figure 11 show scatter plots of the correlation between the QuickSIN test SNR loss and the UCAMST SNR_20% and SNR_80% results.

Variable Name	**SNR_20%**	**SNR_80%**	**AVE at SNR_20%**	**IOI-HA-Average**
Correlation to QuickSIN SNR loss	0.872	0.594	-0.215	-0.060
Statistical significance	< 0.001	0.054	0.526	0.861

***Table 10*. Correlation of QuickSIN test SNR loss with potential covariates**

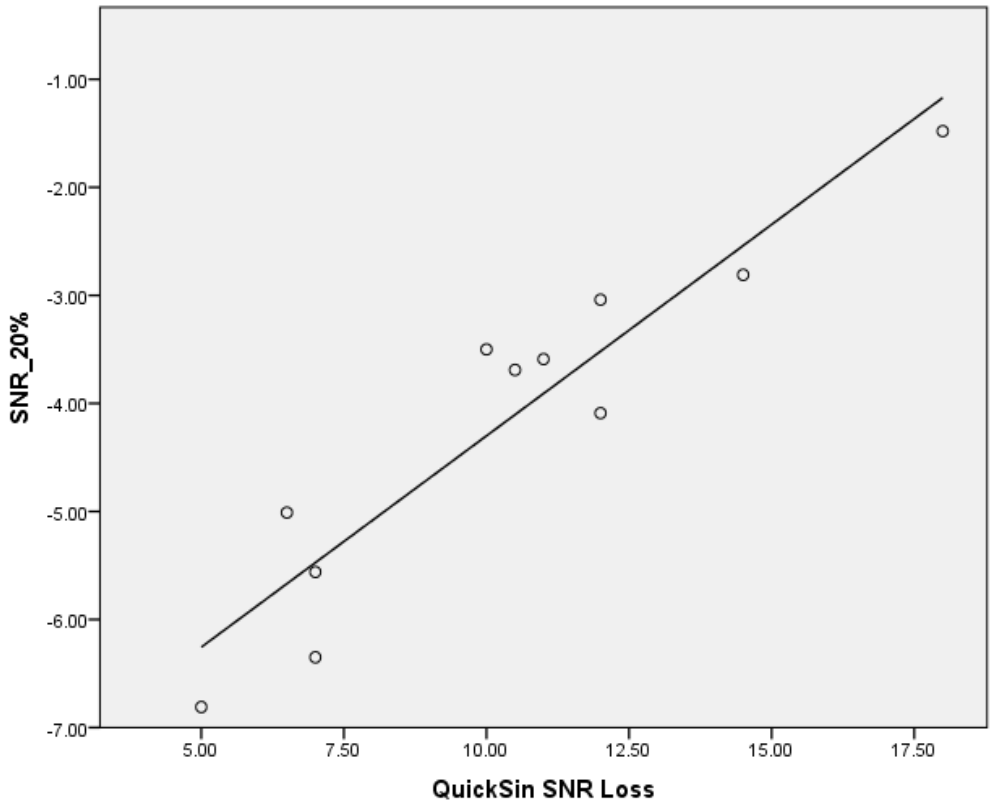

***Figure 10*. Scatter plot correlation of QuickSIN test SNR loss and UCAMST SNR_20%**

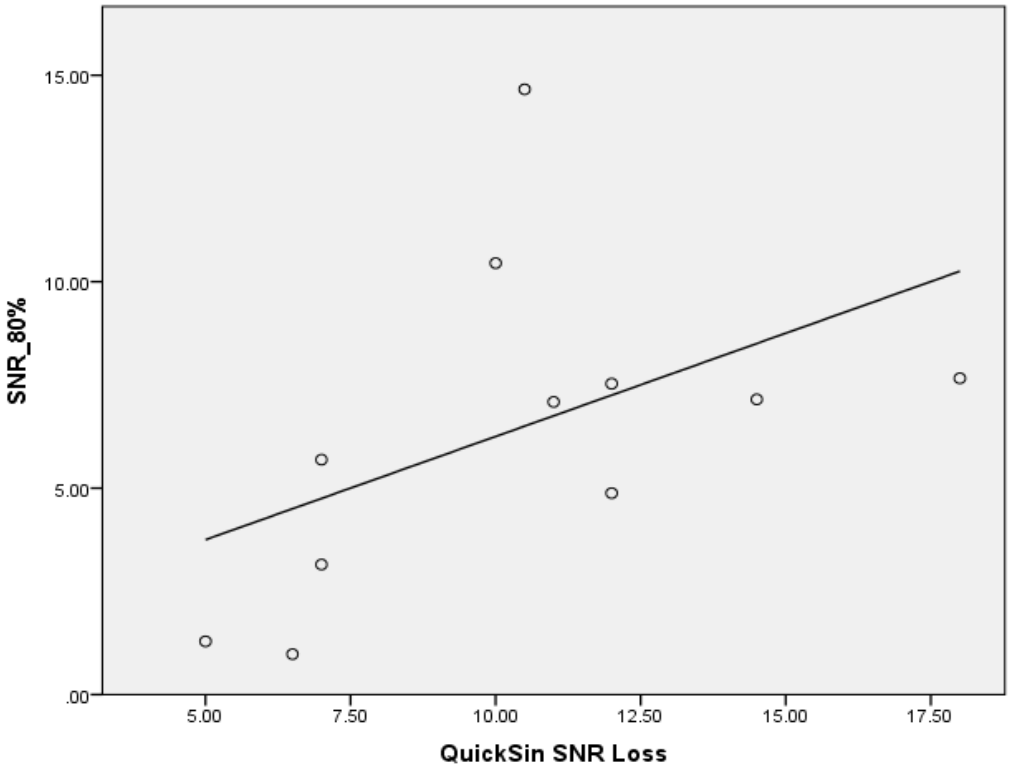

***Figure 11*. Scatter plot correlation of QuickSIN test SNR loss and UCAMST SNR_80%**

The lack of correlation between QuickSIN test SNR loss results and the study predictor or outcome variables, shown in Table 10, justified not including QuickSIN test SNR loss as a partial correlation control covariate in the correlation analysis reported in Table 8.

3.7 Results summary

After removing outliers, the study results included data from 11 participants for analysis. The small sample size required that a Spearman non-parametric approach was used for correlation analysis.

Analysis of covariates showed that no extraneous variables were significantly related to the study predictor or outcome variables. Hence, partial correlation analysis was not required.

The present study hypothesised that "Better auditory-visual enhancement in noise is related to self-reported hearing aid outcomes". In addition, section 1.6 described speculative interpretations of literature by the author regarding the possibility that hearing aid benefit and satisfaction might be related to AVE in opposite directions.

The most important outcome variable IOI-HA-Average was not significantly related to the study predictor variable AVE. The outcome variable "IOI-HA-Q2 Benefit" was not significantly related to the study predictor variable AVE. The outcome variable "IOI-HA-Q4 Satisfaction" was not significantly related the study predictor variable AVE. The study results were unable to support the study hypothesis due a lack of statistical significance in the analysis of the results. The study results were unable to support the speculation in section 1.6 regarding opposite relationship directions between AVE and hearing aid benefit and satisfaction.

SNR loss as measured by the QuickSIN test is strongly related to the UCAMST SNR_20% results.

4 CHAPTER FOUR: Discussion

4.1 Introduction

The main goal of the present study was to measure whether auditory-visual enhancement (AVE) was related to hearing aid outcomes in older adults. Findings from this study were inconclusive due to the small size of the participant group. All results showed a flat to positive correlation trend between AVE and all hearing aid outcomes. In the author's opinion, the trends were large enough to warrant further studies into these relationships. During the present study, a number of observations were made which will assist future studies. This chapter will discuss results and findings in relation to expectations from literature, and will also discuss limitations and directions for future studies. Clinical implications cannot currently be determined due to the inconclusive results of the present study, but may become clearer after the completion of future studies.

4.2 Methodological observations

During the various stages of the present study, observations were made regarding the study methodology that may have affected the results. These observations are discussed for the purpose of allowing confidence in the results to be assessed, and to enable future studies to consider whether to take to the same approach or an alternate one. These observations are not necessarily limitations of the study, which are described separately later in this chapter.

4.2.1 Participant confidence in their lipreading ability

During the recruitment and testing of participants, their confidence in their lipreading ability was an issue that needed to be managed by the researcher. Candidate participants who thought they could not lipread were reluctant to volunteer or make a testing appointment date.

The researcher built up the confidence of candidate participants who expressed interest in the study to assist them to feel comfortable enough to make a testing appointment. The researcher told candidate participants that they probably lipread better than they thought and that being a good lipreader was not a pre-requisite to participating in the study.

Before the auditory-visual test at the UCSHC and especially before the visual-alone portion of the UCAMST, the researcher boosted the participants' confidence by encouraging guessing and saying that being wrong did not matter. The researcher praised correct visual-alone responses and sometimes said what the correct answers were when the participant did not respond at all. Such researcher behaviour could significantly affect scores (especially visual-alone) because otherwise some participants had a tendency to become silent and give up after having some early difficulty. After the confidence boosting words from the researcher, the participants usually became re-engaged in repeating what they thought had been said by the UCAMST.

4.2.2 Testing appointment duration

Many of the participants were more than 80 years old and could easily become tired after concentrating for some time. This phenomenon was expected and was considered when the study testing protocols were designed. The goal was to keep clinic testing time to a duration of two hours or less, and most testing sessions at the UCSHC took approximately this long. In addition, the testing was sequenced so that the most important tests that might support or refute the study hypothesis were administered early in the appointment. Tests for control covariates were administered next and the QuickSIN test was administered last. Many participants openly said that they were tired well before the QuickSIN test. Some participants said that they were tired only twenty minutes into the testing session during the auditory-visual tests. They found repeating three sets of 15 sentences for the auditory-alone, auditory-visual, and visual-alone conditions to be tiring. By comparison, the

QuickSIN test (which only tests in the auditory-alone condition) uses three sets of six sentences with one set being for practice and then two test sets. Ideally, the duration of testing appointments in the present study should have been limited to one hour. Similarly, testing using the UCAMST would have been halved in duration, taking into account time spent for loudness scaling and practice.

4.3 Study hypothesis results

The study hypothesis was that better auditory-visual enhancement in noise would be related to self-reported hearing aid outcomes. In addition, section 1.6 described speculative interpretations of literature regarding the possibility that the hearing aid outcomes "benefit" and "satisfaction" might be related to AVE in opposite directions.

Results in Table 8 showed that the global hearing aid outcome variable, IOI-HA-Average, had a correlation of $r_s = 0.440$ and a significance of $p = 0.175$ with the study predictor variable AVE. The study results do not support the study hypothesis due a lack of statistical significance (17.5% chance of the population correlation being zero). A nonsignificant positive trend between the outcome variable IOI-HA-Average and the predictor variable AVE was observed. The lack of statistical significance may be due to the under sized participant group of 11 member. The statistical power calculation mentioned in section 1.9.4.2 showed that at least 29 participants were expected to be required.

If the population correlation was the same as the present study's sample group of participants correlation of $r_s = 0.440$, then the effect size would be $r^2 = 0.194$. This would suggest that 19.4% of the variation in the hearing aid outcome variable IOI-HA-Average could be accounted for by variations in the predictor variable AVE.

While the study results were inconclusive, a number of observations were made which will assist future studies. The author was of the opinion that the correlation of the AVE predictor with the IOI-HA-Average outcome was high enough to warrant further studies into these relationships. Future studies using the below recommendations for study designs should be able to confirm if a relationship does indeed exist. In particular, increasing the number of participants should be the main factor in possibly achieving statistically significant results.

The results for the hearing aid outcome variables "IOI-HA-Q2 Benefit" (*"Think about the situation where you most wanted to hear better, before you got your present hearing aid(s). Over the past two weeks, how much has the hearing aid helped in those situations?"*) and "IOI-HA-Q4 Satisfaction" (*"Considering everything, do you think your present hearing aid(s) is worth the trouble?"*) were similar to hearing aid outcome variable IOI-HA-Average. The study results were inconclusive with regards to whether a relationship to AVE exists. Both showed a positive correlation trend, as did IOI-HA-Average. It seems unlikely that any statistically significant correlation found in future larger studies would show that the hearing aid outcome "satisfaction" has a positive correlation while the outcome "benefit" has a negative correlation. The results of the present study do not support the author's speculation on these hearing aid outcomes described in section 1.6.

The above analysed the relationships of the predictor variable AVE to selected hearing aid outcome variables. The relationships between AVE and the hearing aid outcome variables are shown in Table 9 in rank order of correlation to AVE. None of the outcomes had a statistical significance of $p < 0.05$. All outcomes showed a positive (greater than zero) correlation trend.

4.4 Predictor and outcome variable results compared to literature

The present study predictor and outcome variable results were be analysed in comparison to the results found in published literature. The following discusses results of the present study from that point of view.

4.4.1 AVE Normalisation

Table 2 shows the measured values for the predictor variable AVE. The means for AVE at SNR_20% (56%) and AVE at SNR_80% (52%) were similar to each other. This confirms that the normalisation formula obtained from literature was appropriate to use in the present study. The normalisation formula (AVE = (AV - A) / (1 - A)) is described in section 1.2.2.1. It normalises raw AVE (AV - A) based upon the possible enhancement above the auditory-alone score (1 - A). While the normalised means were similar, AVE at SNR_80% had a much larger standard deviation (24.1%) than AVE at SNR_20% (14.2%). One possible reason for this is ceiling effects at the louder sound level for SNR_80%. Some participant's audiograms showed phoneme and word repetition scores in the absence of background noise that did not exceed 80% at the loudest presentation levels. Another possible reason is that the normalisation formula multiplies AVE scores at SNR_80% by five (i.e. they are divided by 1 - 0.8 = 0.2), whereas those at SNR_20% are only multiplied by 1.25 (1 – 0.8 = 0.8). The raw AVE scores at SNR_80% were small numbers that were multiplied by five, and hence any small random error in test results was expanded.

4.4.2 AVE magnitude

Section 1.3.2 mentions a study by Ma et al. (2009) where participants with normal hearing and vision improved auditory-alone scores of 15% at -12 dB SNR, to score 60% in the auditory-visual condition. That result is a raw AVE of 45% (which normalises to 52.9%). The present study used an auditory-

alone score of 20% correct and produced a raw AVE of 44.8% (which normalises to 56%). The results from the present study were similar to the results of the study by Ma et al. (2009).

The difference in the percent correct used for the present study (20%) and the study by Ma et al. (2009) (15%) is not expected to make a substantial difference in results. Both are near the auditory-alone percent correct that is expected to results in the maximum AVE. This expectation was confirmed by the results for raw AVE at SNR_20% and raw AVE at SNR_80% in the present study. Raw AVE at SNR_20% was much larger (44.8%) than raw AVE at SNR_80% (10.4%).

4.4.3 UCAMST results compared to QuickSIN test

Table 2 shows the mean measured values for SNR_20% and SNR_80% for the group of participants in the present study. The measurement for SNR_20% was -4.2 dB and for SNR_80% was 6.4 dB. Comparing these results to data from published studies provides another verification of the UCAMST, present study test methods, and whether the participant group's characteristics were similar to past studies. Ma et al. (2009) reported that a SNR of -12 dB resulted in 15% of words correct in young university students with normal hearing. One would expect that 20% correct would have been achieved at a slightly higher (less negative) SNR than the 15% correct in the Ma et al. (2009) study. Results in Table 5 showed that the QuickSIN test reported a mean SNR loss of 10.3 dB for the present study's participant group. Taking 10.3 dB off the UCAMST SNR_20% measure of -4.2 dB suggests that the average normal hearing person would have a SNR_20% of -14.5 dB measured by the UCAMST. This calculated result is similar to the -12 dB for 15% correct reported by Ma et al. (2009). However, the -14.5 dB calculated value is not slightly higher than the -12 dB result, as was expected by the use of 20% of words correct rather than 15% correct.

Tests of normal hearing participants by the team developing the UCAMST using the auditory-alone mode of operation, showed that they had a mean SNR_20% of -11.6 dB (Stone, 2016). This SNR of -11.6 dB is very similar to the SNR of -12 dB found by Ma et al. (2009) even though there were differences in test methods. The study by Ma et al. (2009) used a test method where participants were asked to recognise and write down individual words presented in noise. The UCAMST used matrix sentences that have a more closed set of words that were verbally repeated by participants. In addition the study by Ma et al. (2009) measured SNR at 15% correct rather than the SNR_20% used for the UCAMST.

The above calculation used a SNR loss of 10.3 dB measured using the QuickSIN test in the present study. This measurement matches the findings of Lavie et al. (2014) who compared the speech-in-noise performance of a group of older adults with hearing impairment to a group of young adults with normal hearing. The older group required a SNR that was 10 dB greater than the younger group for all percentage of words correct levels tested. The mean audiogram and age range of the older adult group (average age 76.3 years, SNHI of 30 to70 dB at 500 to 4000 Hz, mean four frequency PTA of 50.94 dB) was similar to the participant group of present study. However, a study by Grant and Walden (2013) found that pure tone thresholds and unaided word recognition in quiet results from the audiogram, were of marginal use in predicting speech understanding in background noise by participants with hearing impairment with or without amplification.

In summary, the participant SNR performance reported by the UCAMST in the auditory-alone condition and by the QuickSIN test in the present study were consistent with each other and with data from published studies.

4.4.4 IOI-HA result norms

Results in Table 4 showed that all results for the IOI-HA questionnaire in the present study were within one standard deviation of the published norm means. Such alignment between the present study's results for hearing aid outcome variables and published data, provides further confidence regarding the representative nature of the participant group's characteristics.

4.5 Control covariate results discussion

Section 1.8 of the Introduction chapter describes various findings from literature with regards to control covariates that were expected to be related to the outcome or predictor variables of the present study. Based on this literature, several tests were included in the present study's test protocols to collect data on control covariates. In general, analysis of the covariate results did not show significant relationships between the covariates and the outcome and predictor variables of the present study, based on a significance level criterion of $p < 0.05$. The most significant covariate had a significance of $p = 0.083$. This lack of statistical significance in covariate relationships may be due to the under sized participant group of 11 member. The statistical power calculation mentioned in section 1.9.4.2 showed that at least 29 participants were expected to be required. The following discusses present study results for each of the covariates in more detail.

4.5.1 Visual acuity

Table 5 shows the range of measured values for visual acuity. A wide range of visual acuity test results were observed among participants. The results ranged from 20/25 feet to 20/60 feet. Normal vision is considered to be 20/20 feet (Hetherington, 1954). Hence the participant with the worst distance vision could just see at 20 feet what a normal seeing person would see at 60 feet. The participant with the best distance vision could just see at 20 feet what a normal seeing person would

see at 25 feet. Participants were tested with their eye glasses worn if they reported that they normally conversed with people while wearing their glasses. As described in section 1.8.5, previous studies have screened for visual acuity and excluded candidate participants whose acuity was worse than 20/30 feet in some studies and 20/40 feet in other studies. The present study included participants with all visual acuity results and used these results as a control covariate. Surprisingly, the visual acuity results were not significantly related to the AVE predictor variable with $r_s = 0.234$ and $p = 0.489$ (from Table 7) or with vision-only speech understanding results with $r_s = 0.117$ and $p = 0.732$. Visual acuity was also not significantly related to the IOI-HA-Average global hearing aid outcome variable with $r_s = 0.471$ and $p = 0.143$ (from Table 6). However, the correlation trend of $r_s = 0.471$, while statistically not significant, leaves open the possibility that a relation may be shown in a larger study.

One might have expected a close relationship between visual acuity and AVE. If AVE were related to hearing aid outcomes, one would then expect visual acuity to have a present but a lesser relationship to hearing aid outcomes. The measured data does not support the existence of a relationship between visual acuity and AVE or visual-alone speech understanding results. A relationship to hearing aid outcomes may exist.

One would expect that at some level of poor visual acuity, there would be a relationship between visual acuity and visual-alone speech understanding ability and hence a relationship to AVE. However, within the present study's group of participants' range of visual acuity, no relationship was found. This finding is encouraging with regards to the potential future use of vision-related testing and vision-related training in audiology. It suggests that gains in speech understanding in noise that come from observing the lips of the person talking are not limited to the those who have excellent vision. The segment of the population with the greatest hearing impairment is the elderly (Lemke, 2011). Many elderly people do not have excellent visual acuity (Sjöstrand et al., 2011). The results of the

present study suggest that poor vision was not a barrier for the elderly to gain the benefits of visual information while listening to speech-in-noise. The level of poor visual acuity that would be a barrier for the elderly to gain the benefits of visual information while listening to speech-in-noise, was not determined by the present study.

4.5.2 Reading span test

Table 5 shows the mean measured results for the RST. Participant reading span was measured to estimate cognitive working memory skills. As described in section 1.8.4, published studies have shown that working memory is one of the factors most closely related to the ability to understand speech-in-noise. As such, working memory was selected as a control covariate for the present study. The RST result used for covariate control was the result with two or more sets of sentences correct. This covariate correlated with the IOI-HA-Average global hearing aid outcome with $r_s = 0.54$, $p = 0.083$. It correlated with AVE with $r_s = 0.405$, $p = 0.217$. Neither of these correlations met the required significance of $p < 0.05$.

Reading span was selected as a control covariate based on literature that showed that working memory is one of the factors most closely related to the ability to understand speech-in-noise. However, the present study variables AVE and IOI-HA-Average were not the same as measuring the ability to understand speech in background noise. The variable in the present study that was most similar to the variables measured in RST literature was SNR_20%. Participants who have a better speech understanding in background noise are expected to have a SNR_20% score that is a larger negative number than those with worse speech understanding in background noise. Hence a negative correlation is expected between SNR_20% and RST scores. A correlation analysis of RST scores with SNR_20% showed $r_s = -0.337$, $p = 0.311$. The correlation was negative as expected but did not meet the required significance of $p < 0.05$.

While the correlations in the present study using the RST results were not statistically significant, it is useful to compare the size of the correlation to findings from literature. RST results themselves often cannot be compared between studies due to methodological difference. The present study used the original RST procedure in the study by Daneman and Carpenter (1980). Literature regarding hearing in noise often used the RST procedure used in the study by Ronnberg et al. (1989). The Daneman and Carpenter (1980) test procedure was selected for the present study because of its simplicity based on written cards. The Ronnberg et al. (1989) test procedure used in literature requires the use of specialised computer software. Apparent advantages of the Ronnberg et al. (1989) test procedure are that the result is out of 54 for final words in sentences and also measures whether participants understand the sentences they read. The disadvantage of the Daneman and Carpenter (1980) test procedure is that most participants score a reading span of two (out of a possible six) with a few scoring three or zero (see Table 5). A test with a result out of 54 should have a spread of results between participants, even when there are only small differences between their abilities. A test with a result out of six and where most participants score either two or three cannot detect small difference between the abilities of participants. This lack of results spread in the present study reduces the ability of the RST to detect small to moderate differences in working memory between participants.

Accepting that the RST results of the present study cannot be directly compared to most studies in the literature, one can compare the correlations found between reading span (using any test method) and the ability of participants to understand speech-in-noise. The present study found a statistically nonsignificant correlation between reading span (working memory) and:

1. IOI-HA-Average: $r_s = 0.54$,

2. AVE: $r_s = 0.405$,

3. SNR_20%: $r_s = -0.337$.

By comparison Arehart et al. (2013) showed that working memory accounted for 29.3% of the variance in intelligibility scores. That calculates to $r = 0.541$. Similarly, Ng et al. (2013) found that reading span was related to various speech in quiet and speech noise repetition tasks with correlations ranging from $r = 0.39$ to $r = 0.58$ depending upon the particular test method used. The correlations found between working memory as measured by the RST and participant performance with speech-in-noise in the present study, were similar to the correlations found in literature.

The present study did not use reading span as a control variable in statistical analysis due a lack of statistical significance. However, with a larger group of participants or a more sensitive test method, the statistical significance may meet the threshold of $p < 0.05$. Published studies found the statistical significance necessary to require that RST results be controlled for and the present study found correlations of a similar size to these published studies. Hence, future studies into the relationship between AVI and hearing aid outcomes should continue to measure and potentially control for working memory as measured the RST. A different type of RST than that used in the present study should be considered to achieve greater sensitivity through a larger spread of RST results. The present study had a reading span result of two for most participants with a few participants scoring three or zero. If an alternate test method had larger number mean result, this should ensure a larger spread of results and hence greater sensitivity and statistically more significant results.

4.5.3 Age of hearing impairment onset

As described in sections 1.4.3.1 and 1.8.8, some literature had suggested a possible relationship between the age of hearing impairment onset and the ability of participants to make use of visual information when listening to speech-in-noise. The present study found that hearing impairment onset

age was correlated to the IOI-HA-Average global hearing aid outcome with $r_s = 0.227$, $p = 0.501$. Correlation to the predictor variable AVE was $r_s = 0.101$, $p = 0.767$. Hence, the present study found no significant relationship between hearing impairment onset age and the study outcome and predictor variables. As described in section 1.4.3.1, the study by Tillberg et al. (1996) showed that visual-alone ability may be improved when the hearing impairment onset age was less than 8 years. However, when the onset age was more than 16 years, the acquisition of hearing impairment did not improve visual-alone ability. The minimum age of participant hearing impairment onset in the present study was 20 years. This could explain the present study results that showed no significant relationship between hearing impairment onset age and the study outcome and predictor variables.

4.5.4 MoCA

As discussed in section 1.8.4, studies in literature have found a relationship between dementia or mild cognitive impairment and study predictor variable AVE. The present study measured mild cognitive impairment using the MoCA and found a correlation to AVE of $r_s = -0.386$, $p = 0.241$. The correlation did not pass the test of statistical significance ($p < 0.05$). The negative correlation trend suggested that participants with poorer MoCA scores (more cognitive impairment) had better AVE scores. This is the opposite to the result one might expect and is unexplained. The majority of participants in the present study (64%) had abnormal MoCA scores.

A MoCA adjusted score of less than 26 is considered to be abnormal. The mean MoCA adjusted score for the participant group was 25.5 and hence is considered be abnormal. Only four of the 11 participants in the present study returned a normal MoCA adjusted score. This could be caused by the age of the participants in the present study. The mean age was 77.9 years and ranged from 65 to 86 years. The researcher noted that the participants tended to have difficulty with the memory related tests of the MoCA. The MoCA does not have different normative data for persons in different age

groups and hence the cut off score is not age dependent. A study by Oren et al. (2015) found that 42% of older elderly had MoCA results below the normal cut off score. A study by Pendlebury et al. (2015) found that for hospital patients aged 75 years and above, 30% to 40% (depending on the specific test type and cut-off score used) were found to have a cognitive disorder without having a known dementia/delirium condition. The present study's MoCA test results were consistent with these studies.

4.5.5 UCAMST visual-alone test

As shown in section 3.5.1, the visual-alone results were significantly related to the study predictor variable AVE. The correlation was $r_s = 0.656$, $p = 0.028$. However, visual-alone results were not significantly related to hearing aid outcomes with a correlation of $r_s = -0.034$, $p = 0.92$. Visual-alone results were not controlled for in the correlation analysis of either the study predictor variable (AVE) or the study outcome variables (hearing aid outcomes). This was because visual-alone results were not an extraneous variable but were measured as part of the auditory-visual testing. The significant correlation relationship to AVE is expected because one would expect, when given access to visual information, a participant with good visual-alone ability would enhance their auditory-alone score by more than a participant with poor visual-alone ability. The lack of any trend in the relationship between visual-alone scores and hearing aid outcomes is interesting. If hearing aid outcomes were related to AVE, and if AVE were significantly related to visual-alone test scores, one might have expected some relationship between hearing aid outcomes and visual-alone scores. However, such a relationship was not observed in the present study.

Section 1.5 describes studies in literature regarding possible uses for auditory-visual testing with regards to selecting rehabilitation strategies. The study by Grant, Walden, and Seitz (1998) suggests that test results showing poor AVI performance (measured using AVE) might lead to a

recommendation for auditory-visual training and practice, but that poor visual-alone performance might lead to a recommendation for eye glasses. The present study observed a significant relationship between visual-alone results and the study predictor variable AVE. This suggests the possibility that hearing aid outcomes could be improved through rehabilitation training that improves auditory-visual integration skills but that training in visual-alone lipreading would not improve hearing aid outcomes. The large variation in AVE and visual-alone test scores between participants measured by the UCAMST suggests that the UCAMST could be of use to select audiology clients for the rehabilitation pathway recommendation options described in the study by Grant, Walden, and Seitz (1998) and summarised in section 1.5.2.

4.5.6 QuickSIN as predictor of hearing aid use

Section 1.8.2 mentions literature regarding the QuickSIN test as a predictor of hearing aid outcomes. The prospective study by Robertson, Kelly-Campbell and Wark (2012) found that SNR loss measured by the QuickSIN test was the best predictor of hearing aid purchase and usage (not hearing disability) in the first year following hearing aid fitting. In that study, participants with the greatest SNR loss were more likely to purchase hearing aids and to continue wearing them. The present study did not measure exactly the same hearing aid outcome as the study by Robertson, Kelly-Campbell and Wark (2012). However, the present study did measure SNR loss using the QuickSIN test and also assessed daily usage hours in the study specific questionnaire. The author could hypothesise that daily usage hours might be related to QuickSIN test results in a similar way to the study by Robertson, Kelly-Campbell and Wark (2012) that found that ongoing usage after one year was related to SNR loss using the QuickSIN test. One might expect a larger SNR loss (poorer speech understanding in noise) to be related to more daily hours of hearing aid use. The present study found that SNR loss measured by the QuickSIN test was related to hearing aid daily usage hours with $r_s = -0.319$, $p = 0.339$. The

result is not statistically significant using a criterion of $p < 0.05$ and the negative correlation trend is in the opposite direction to the author's hypothesis drawn from the study by Robertson, Kelly-Campbell and Wark (2012). A study by Walden and Walden (2004) that was referenced by the Robertson, Kelly-Campbell and Wark (2012) study also analysed these relationships. This was analysed in further detail as follows.

The study by Walden and Walden (2004) showed that participants with greater SNR loss had poorer hearing aid outcomes than the participants with smaller SNR loss (a negative correlation of $r = -0.34$). However this correlation decreased and became nonsignificant once age was accounted for. This is because SNR loss typically becomes worse with increasing age. In the Walden and Walden (2004) study, as in the present study, SNR loss was measured by the QuickSIN test and hearing aid outcomes were assessed using the IOI-HA scored using the IOI-HA-Average global hearing aid outcome.

In light of the findings by Walden and Walden (2004), the results of the present study were further analysed. SNR loss measured by the QuickSIN test was correlated with the IOI-HA-Average outcome. The result was a nonsignificant correlation of $r_s = -0.060$, $p = 0.861$ using Spearman correlation. Controlling for age was not possible using the graphical user interface for the non-parametric Spearman correlation in SPSS. The results of the present study were not statistically significant. Unlike Walden and Walden (2004), the present study showed no significant relationship between SNR loss and the IOI-HA-Average outcome.

The study by Walden and Walden (2004) found that participant age was a predictor of the IOI-HA-Average global hearing aid outcome, and then used age as a control covariate for the correlation analysis of the SNR loss predictor variable with hearing aid outcomes. In light of this finding, the results of the present study were further analysed. The relationship between participant age as predictor of the IOI-HA-Average global hearing aid outcome and of daily usage hours was correlated.

The Spearman correlation showed no significant relationship and no nonsignificant trend. Age was related to IOI-HA-Average global hearing aid outcome with $r_s = 0.090$, $p = 0.792$, and age was related to daily usage hours with $r_s = -0.141$, $p = 0.679$.

Published studies such as Robertson, Kelly-Campbell and Wark (2012) have shown that SNR loss measured by the QuickSIN test is one of the best predictors of hearing aid outcomes. In the present study, QuickSIN test results were most closely related to the "daily usage hours" hearing aid outcome ($r_s = -0.319$, $p = 0.339$) but were not related to the IOI-HA-Average global hearing aid outcome. By comparison AVE showed the largest correlation to IOI-HA-Average hearing aid outcome with a nonsignificant correlation of $r_s = 0.440$, $p = 0.175$. In the present study, AVE was a better (but not statistically significant) predictor of hearing aid outcomes than SNR loss measured by the QuickSIN test. This aligns with the findings of Corthals et al. (1997) regarding the relationships between the unaided hearing disability outcome variable and the AVI and noise susceptibility predictor variables explained in section 1.4.1.

4.6 Replacing the QuickSIN test with the UCAMST

The present study had multiple objectives. One of those objectives was to measure SNR loss to help determine if the UCAMST could replace the QuickSIN test in routine clinical test protocols. The SNR loss of participants was measured using the QuickSIN test. These results were compared to results from the UCAMST.

The QuickSIN test estimates the SNR required by a participant to achieve 50% of words correct (Etymotic Research, 2006). The UCAMST outputs two SNR values in the auditory-alone condition. These are SNR_20% and SNR_80%. The UCAMST SNR required by a participant to achieve 50% of words correct can be estimated by calculating the mean of SNR_20% and SNR_80%. The present

study did not use such a calculated SNR_50% to compare to QuickSIN test results. Future studies could compare UCAMST SNR_50% to QuickSIN test results. As discussed above, SNR_20% was a more reliable measure than SNR_80%. Hence, further analysis was based on SNR_20%.

Results in Tables 9 showed that the QuickSIN test SNR loss results were related to the UCAMST SNR_20% results with correlation $r_s = 0.872$, $p < 0.001$. Note that for SNR_80% $r_s = 0.594$, $p = 0.054$ which is just outside the limit for statistical significance of $p < 0.05$. Another check on the similarity of SNR loss measured by the QuickSIN test and SNR_20% is that the mean participant SNR_20% result was -4.2 dB. The mean participant had SNR loss measured by the QuickSIN test of 10.3 dB. This suggests that normal hearing participants would be expected to have SNR_20% of -4.2 – 10.3 = -14.5 dB. Tests of normal hearing participants by the team developing the UCAMST showed that they had SNR_20% of -11.6 dB. The calculated value of -14.5 dB is not dissimilar to the measured value of -11.6 dB. These results suggest the potential for a consistent mapping between SNR_20% and SNR loss measured by the QuickSIN test.

The results of the present study suggest that SNR_20% reported by the UCAMST may be able to replace the need for QuickSIN testing. To confirm this would require a future study to compare UCAMST and QuickSIN test results for other populations of participants.

4.7 Limitations

The present study's methodology had a number of limitations that may have affected the results. Interpretation of results from the present study should be made in light of these limitations and future studies should be designed to avoid some of these limitations.

4.7.1 Too few participants

The main limitation of the present study was that the participant group was too small. Analysis at the beginning of the study suggested that 29 participants would be required to produce statistically significant results. Only 11 participants were included in the statistical analysis of study results. Most of the relationships found did not meet the significance level criteria of $p < 0.05$. Two options are available to remedy this limitation.

One option is to enrol participants from other audiology clinics in addition to the UCSHC. The present study attempted to do this but ethical and logistical considerations made working with private clinics impractical in the absence of longer term planning and preparation.

The other option is to loosen the candidate participant screening criteria. A total of 141 candidate participants were identified in the UCSHS client database before considering other criteria. After considering audiometric criteria, the absence of paper files, or lack of consent for research, only 48 candidate participants were eligible to be invited to participate in the study. A 20% response rate to research invitations was expected. Hence, to enrol 29 participants required that at least 145 candidate participants be sent letters of invitation. The first audiometric criterion to loosen would be the air bone gap criteria. The next criterion would be the slope of the hearing impairment. After that, the minimum acceptable age of participants could be lowered. The negative consequence of loosening the participant enrolment criterion is that the participant group would become less homogeneous. This creates the possibility that relationships found between predictor and outcome variables could be partly the result of random effects of differences between participants. Determining the unique contribution of predictor variables to the outcome variables would then require greater use of statistical covariate control for the differences between participants. That would create risk of reducing the statistical power in the study. Alternatively, a larger and less homogeneous group of

participants can be included in future studies and then statistical analysis can consider the group as a whole and also separately analyse subset groups with more homogeneous characteristics.

4.7.2 Insufficient practice before scoring UCAMST results

Another limitation was that participants had no opportunity for practising listening to matrix sentences in noise before scored testing began. Participants practised repeating six to eight matrix sentences heard without noise during the loudness scaling part of the test procedure. They also heard masking noise without speech during the loudness scaling procedure. This was in contrast to the approach for the QuickSIN test in the present study. The present study QuickSIN test presented participants with at least one full practise set of sentences followed by two scored sets of sentences.

In the present study, participants did not practise with a full set of 15 auditory-alone sentence tests because this would have taken too long and the test protocol was already challenging participants' concentration span. In contrast, MSTs developed in studies for other international languages commonly used seven or eight lists of 20 sentences to allow performance improvement due the learning effect (see section 1.1.6.3) to stabilise (Dietz et al., 2014; Hochmuth et al., 2012; Wagener, Josvassen & Ardenkjoer, 2003). However, participant SNR performance in these international language studies did not improve significantly after two lists of 20 sentences were administered (Dietz et al., 2014; Hochmuth et al., 2012; Wagener, Josvassen & Ardenkjoer, 2003).

In the present study, the researcher observed that participants performed poorly when first repeating the matrix sentences they heard during loudness scaling. This was probably due to the issues around listening to loud speech under headphones described in section 4.7.12.4. In agreement with that description, some participant audiograms showed maximum words and phonemes correct well below 100% even at the loudest levels tested in silence. The researcher observed that after several

presentations of matrix sentences without noise during loudness scaling, participant ability to correctly repeat the sentences improved. Participants would learn the structure of the matrix sentences. For example they would learn that the first word was always someone's name and they became familiar with the list of available names. This improvement in performance may have continued after scored testing had begun. It seems likely that performance in noise would also improve from when the first scored sentence was heard (which was the first time a matrix sentence had been heard in noise). Improving performance during scored testing could make the measured AVE appear larger than it really is because auditory-visual testing followed auditory-alone testing. However, if participant performance improvement ceased early in the auditory-alone set of 15 sentences, then this improvement would have little effect on the AVE measured by the UCAMST. Based on measurements of the learning effect from the international language studies mentioned above, it seems likely that participants in the present study would have continued to improve their performance for two complete lists of 15 UCAMST sentences. Two lists of sentences covered both the auditory-alone and auditory-visual tests in the present study.

4.7.3 No testing before hearing aid fitting

The current study was limited to a retrospective approach using a group of experienced hearing aid user participants. As described in section 1.9.4.1, a prospective study design would have allowed the UCAMST's ability to predict hearing aid candidacy to have been assessed. Any statistical relationships between predictor and outcome variables found in the present study cannot be reliably extrapolated to a diagnostic purpose because the experience of wearing aids may have changed the relationships that existed prior to the fitting of hearing aids.

4.7.4 IOI-HA had only eight questions

As described in section 1.9.3, the IOI-HA questionnaire has been shown to have strong psychometric properties and has been used extensively in research. One of the advantages of the IOI-HA is that it is a short form with only eight questions for participants to answer and hence can be speedily completed. Seven of the eight questions are about hearing aid outcomes. The disadvantage of the IOI-HA is that a short questionnaire may produce less reliable and valid results than a long questionnaire (Rolstad, Adler & Rydén, 2011). The results obtained from the IOI-HA can be used as a global average of the seven hearing aid outcomes or each of the seven questions can analysed separately, which provides a total of eight outcomes to analyse. Analysing eight outcomes with a small group of participants (11 participants in the present study) increases the probability that some of the relationships found between the predictor variable and outcome variables were the result of chance rather than a relationship that applied to the population (Field, 2013).

The Abbreviated Profile of Hearing Aid Benefit (APHAB) is another questionnaire regarding hearing aid outcomes (Cox & Alexander, 1995). It has 24 items for participants to answer and is administered before and after hearing aid fitting. The APHAB results should be more reliable and valid than the IOI-HA due to the larger number of questions. However, the APHAB is designed to be used in a prospective study before, and then again after hearing aids are fitted, hence the IOI-HA was more suitable for the retrospective-only design of the present study.

4.7.5 Some participant HA settings more ideal for AVE

As described in section 1.8.11, AVE can be affected by the hearing aid technology and settings. Data were gathered from participant paper files regarding their hearing aid technology and settings. The purpose of such data collection was to allow for the possibility of controlling statistical analysis for hearing aid technology and features covariates. During participant testing, the planned data were

collected from paper files. However, many participant files had very little information available. Hence, these data were not used for controlling statistical analysis or any other purpose. This created the possibility that some of the hearing aid outcome results were partly related to hearing aid technology and setting covariates that were not controlled.

4.7.6 Manual dexterity not measured

Participant manual dexterity was not measured as a control covariate in the present study. Manual dexterity is one of the factors that influences hearing aid candidacy, ongoing use, satisfaction, and perceived performance (Dillon, 2012; Kumar Hickey & Shaw, 2000). This relationship is strongest for the "behind the ear" style of hearing aid (Kumar Hickey & Shaw, 2000) worn by most the participants in the present study. It is possible that manual dexterity influenced the hearing aid outcomes of participants in the present study and that this covariate should have been controlled. Manual dexterity was not measured due to the difficulty in accurately measuring it using, for example, the "Purdue pegboard test" (Kumar Hickey & Shaw, 2000).

4.7.7 Mental speed of processing not measured

Participant cognitive "speed of processing" was not measured as a control covariate in the present study. As described in section 1.8.4, literature showed that "speed of processing" and "working memory" were the cognitive skills with the greatest relationship to the ability to understand speech-in-noise. The RST was used to assess cognitive "working memory" but no test was included to assess cognitive "speed of processing". It is possible that cognitive "speed of processing" influenced the AVE predictor variable of participants in this study and that this covariate should have been controlled. The covariate "speed of processing" was not measured due to complexity and test time taken to measure it.

4.7.8 Hearing aid price not recorded

The price paid by participants for their hearing aids was not recorded as a control covariate in the present study. In the expert opinion (not scientific evidence) of the contributors to the round-table discussion by Abrahamson et al. (2005), the price paid for a hearing aid was said to be related to self-reported hearing aid satisfaction and benefit. Paying a lower price was said to be related to higher satisfaction.

Contrary to the expert opinion of Abrahamson et al. (2005), are the finding of the study by Kelly-Campbell and McMillan (2015). The study found that there was no significant relationship between the cost of the hearing-aids to the participants and any Satisfaction with Amplification in Daily Life (SADL) questionnaire score or Measure of Audiologic Rehabilitation Self-Efficacy for Hearing Aids (MARS-HA) questionnaire score. The Pearson r values ranged from 0.067 to 0.139.

It is possible that the price paid for hearing aids influenced the hearing aid outcomes self-reported by the participants in the present study and that this covariate should have been controlled. The price paid for hearing aids by participants also depends upon the level of subsidy available at the time of purchase. No attempt was made to gather data on the hearing aid price, subsidies, or the amount paid by the participant.

4.7.9 Acceptable noise level (ANL) not measured

Participant “Acceptable Noise Level” (ANL) was not measured as a control covariate in the present study. The study by Nabelek et al. (2006) showed that ANL is one of the factors that influences hearing aid candidacy, ongoing use, and overall success. Contrary to Nabelek et al. (2006), a discussion paper by Olsen and Brännström (2014) raised questions about the precision (i.e. repeatability) of ANL test results and concluded that the ANL model for prediction of hearing aid use

had yet to be proven valid. Olsen and Brännström (2014) based their finding on a review of 45 papers published in peer reviewed journals as well as on a number of papers from trade journals, posters and oral presentations from audiology conventions.

It is possible that ANL influenced the hearing aid outcomes of participants in the present study and that this covariate should have been controlled. ANL was not measured due to the participant test time required to measure it and in addition, there is controversy regarding whether or not ANL is a valid predictor of hearing aid outcomes.

4.7.10 Native language not controlled

As described in section 1.8.6, AVE can be affected by whether a participant's native language is the same as the language used in the test material (NZ English). Participant native language was recorded during testing appointments. The purpose of such data collection was to allow for the possibility of controlling statistical analysis for the native language covariate or to provide a potential reason for an outlier result. One participant was not a native English speaker during childhood but spoke excellent English with an accent during the testing appointment. This participant did not produce an outlier result. The native English covariate was not used for controlling statistical analysis or any other purpose.

4.7.11 History of central nervous system events not controlled

As described in section 1.8.10, AVE may be affected by participant CNS events and CNS medication use. Participant CNS events were recorded during testing appointments. The purpose of such data collection was to allow for the possibility of controlling statistical analysis for the CNS events covariate or to provide a potential reason for an outlier result. CNS events were recorded for several participants in the present study. These events were: stroke in one participant, concussion in two

participants, Epilepsy in one participant, Parkinson's disease in one participant. The CNS events covariate was not used for controlling statistical analysis or any other purpose. This creates the possibility that some of the hearing aid outcome results were partly related to CNS events that were not controlled.

4.7.12 UCAMST limitations and enhancements

Several observations were made regarding UCAMST limitations or opportunities for enhancements to the UCAMST. As previously described, one of the objectives of the present study was to provide practical UCAMST usage feedback to its developers. This was done verbally during the study and sometimes resulted in immediate changes to the UCAMST. In particular, the loudness scaling features were added to the UCAMST after initial use of the UCAMST during study protocol development. Once participant testing began, the UCAMST software was not updated to ensure that all participants had the same experience with the UCAMST. The below observations have not yet resulted in changes to the UCAMST. The UCAMST features related to some of these observations are described in more detail in section 1.7.4.

4.7.12.1 The UCAMST was new

The UCAMST was still under development during the present study. The UCAMST was being developed and validated as part of another Master's thesis project (Stone, 2016). Formal participant testing for the present study did not begin until this validation was completed. However, there was limited existing validation, experience, and refinement of the tool at the time of participant testing for the present study. The degree to which this affected the results of the present study, if at all, is unknown.

4.7.12.2 Low context matrix sentences

The UCAMST produces five-word, low context sentences, as do all MST tools. The low context nature of the sentences means that it is difficult to guess a missing word in a sentence based on the known words in the rest of the sentence. Real word sentence are more often high in context. Low context sentence tests in noise are known to disadvantage older people's AVE scores relative to real-world AVE (Sommers, Tye-Murray & Spehar, 2005). From this finding, one could speculate that whatever relationship is found between AVE and hearing aid outcomes in the current study, would be even more pronounced in real-world conditions.

An alternative design for an auditory-visual test tool would be to use a list of stored high context real-world sentences instead of matrix sentences. However, the context in a real-world sentence may come from previous sentences and hence producing sentences with real-world context may not be simple. Testing of hearing in noise and AVI in noise has extensively used MSTs in various languages and is a simple test design that produces many test sentences (Dietz et al., 2014). The in clinic testing experience of the present study did not find any particular reasons that would suggest a change of approach from the use of matrix sentences.

4.7.12.3 Loudness scaling practise with noise

The UCAMST loudness scaling features currently presents speech and noise separately. An enhanced design could add the option of presenting speech and noise together as the scored tests do. This could also be used for participant practise or a separate practise feature could be provided.

4.7.12.4 Loudness level setting

One of the negative consequences of the UCAMST's approach (also used by other MSTs worldwide) of adaptively varying the speech sound level while holding the noise level unchanged, is that the maximum speech sound level sometimes needs to be very loud. The maximum speech sound level is

louder than that required by the QuickSIN test in order to ensure that the lower speech sound levels were still audible. The QuickSIN test uses the sound level “loud but OK”. Exceeding that level may result in an uncomfortably loud sound. As previously described, the author of the present study's experience with the UCAMST showed that the typical maximum reduction in the speech sound level for 20% of words correct in noise is about 15 dB below the sound level setting (the speech sound level setting is also the noise sound level). Ideally the speech sound level for 20% correct would be “loud but OK” which would mean that the speech sound level set in the UCAMST would be 15 dB above “loud but OK”. Such a loud speech sound setting may be uncomfortably loud or may cause other problems explained in the following paragraphs.

Another problem with the above approach used for setting sound levels on the UCAMST is known as the upward spread of masking (Moore, 2012). When a loud sound is presented to the cochlea at a low frequency, this produces an excitation for a range of neurons corresponding to a range of frequencies above and (to a much lesser extent) below the presentation frequency. The headphones used by the UCAMST present a natural speech sound spectrum. When this speech was amplified, all parts of the spectrum were amplified. The amplification of the lower speech frequencies masked some of the higher speech frequencies because of the upward spread of masking. Hence it was desirable to test using the UCAMST at the lowest sound level consistent with other sound level constraints.

Presenting speech at loud levels using headphones with a natural sound spectrum does not result in speech intelligibility results that match speech presented at loud levels using hearing aids with a sound spectrum shaped to a prescription. For a downward sloping hearing impairment, the headphones present excessive levels of low to mid frequency sound which results in the upward spread of masking (Dillon 2012; Moore, 2012) and reduces speech intelligibility. The resultant reduced access to high frequency speech information may make participants more reliant on visual information

during testing than in the real-world using hearing aids that presents low and mid frequency sounds at a lower levels. This could result in higher measured unaided AVE during testing than occurs in the real world with hearing aids.

In using the UCAMST with the group of research participants, the author of the present study sometimes observed difficulties in finding a sound level that was clearly audible at 15 dB below the sound level setting, yet was not uncomfortably loud at the sound level setting.

4.7.12.5 Limit sound level for word stimuli

In addition to the above observations regarding finding an appropriate sound level setting, another excessive loudness issue was discovered. The UCAMST adaptively increased the sound level automatically to find the sound level where a participant achieved 80% of words correct in the auditory-alone condition. This sound level had no upper limit beyond the physical limits of the hardware delivering the sound. Some participants achieved 80% or less of words correct in their audiogram on file at the maximum sound level in a quiet background using the NZAS (2007) test procedure. Hence, the UCAMST may keep increasing the sound level without limit while trying to find the sound level that results in 80% of words correct. The UCAMST should have an upper safety limit on the sound level it may present, relative to the sound level set on the UCAMST user interface.

4.7.12.6 Frequency spectrum shaping

The frequency spectrum of the sound presented by the UCAMST headphones is that of normal human speech with added masking noise. The masking noise used was derived from the speech stimuli itself, ensuring both had spectra equivalent to the long-term average speech spectrum of the female speaker used in the test. This spectrum is different to the sound spectrum heard by participants while using their hearing aids. Candidate participants were only invited to be included in the study if they had a sloping mid to high frequency hearing impairment. Hence the sound spectrum participants heard

through their hearing aids had the mid to high frequencies amplified relative to the sound spectrum heard through the UCAMST headphones. The studies by Tillberg et al. (1996) and Grant and Seitz (1998) showed that maximum AVE occurs for persons with a downward sloping hearing impairment because visual information reveals the most information about high frequency speech sounds. From this one could deduce that participants will achieve a higher AVE unaided while being tested with a natural sound spectrum, than they would achieve in the real word when using their hearing aids. This suggests that future study designs might consider also relating aided AVE to hearing aid outcomes.

A simulation of aided AVE could be measured by the UCAMST before hearing aids were fitted with the addition of software features to the UCAMST. The sound spectrum presented by the UCAMST could be shaped to match the participant's hearing aid fitting. A set of adjustment controls on the user interface could allow the researcher to adjust the gain at octave and inter-octave frequencies to match the hearing aid fitting. In addition, a predicted hearing aid fitting could be modelled by providing a user interface feature to enter an audiogram and hearing aid prescription method. The spectrum presented over headphones would then be the prescription recommendation for the entered audiogram.

4.7.12.7 Displayed face size

The UCAMST computer display screen used in the present study showed a human female face with a breadth of 87 mm. The mean breadth of an adult human female head is 146 mm (Young, 1993). The present study's head breadth was 60% of the mean human female head. This smaller than normal head, face, and lip size could potentially affect participant AVI ability and hence AVE scores. The distance between the participant's face and the computer screen was carefully chosen to mitigate this possible source of scoring error. The mitigation is described in section 1.8.5 along with information

from literature regarding the relationship between viewing distance, face size, and AVI. Based on this information, the displayed face size should not have affected AVE scores in the present study.

A software feature enhancement could be added to the UCAMST to allow the size of the displayed face to be adjusted using a user interface control.

4.8 Directions for future research

No published studies have reported findings on the relationship between the ability to integrate visual information and hearing aid outcomes or candidacy. The present study began research into this important topic. However, the present study was just a first step. Further studies are needed to expand the participant group size, focus research questions on issues and relationships found in the present study, deal with limitations of the present study, and further develop the UCAMST.

4.8.1 Participant practice duration

During the testing appointments of the present study it became evident that participant performance improved during the early stages of testing. Further study is required into how much practice should be provided to participants so that both auditory-alone and auditory-visual performance have stopped improving before scored testing begins. Practice should be provided with speech-in-noise rather than with speech and noise separately. Test time should be kept to a minimum to reduce fatigue in elderly participants. Alternatively, the UCAMST could be designed in such a way that no practise is required and scored testing adaptively takes improving participant performance into account.

4.8.2 Prospective Study

The original scope of the present study included a prospective component. Logistical constraints caused the prospective component to be removed so that the present study was entirely retrospective.

A retrospective study is able to find relationships that may exist between AVI and hearing aid outcomes. However, one of the purposes of finding such relationships in research is to use them during diagnostic testing to guide the selection of clinician interventions and recommendation to clients. A prospective study is required to answer research questions around the diagnostic use of the UCAMST before hearing aids are fitted. This is because the use of hearing aids prior to testing in a retrospective may change relationships that existed before hearing aids were fitted. The APHAB questionnaire is recommended as the way to collect self-reported hearing aid outcomes in a prospective study.

4.8.3 Auditory-visual testing of diverse participant demographic groups

The ultimate goal of finding relationships between AVI and hearing aid outcomes is to assist clinicians with the selection of interventions and recommendation to clients. Those clients would be of a variety of ages and with a variety of hearing impairment degree, type, and configuration. The participants in the present study were screened to a narrow range of ages and hearing impairment degree, type, and configuration. Those narrow ranges were chosen based on findings from literature that were expected to maximise the effect size for the research question and minimise the size of covariate contribution to relationships. Such narrow ranges were appropriate for an initial study seeking to discover if a relationship existed at all. The present study found trends that were not statistically significant. The author is of the opinion that the relationships may become statistically significant if larger numbers of participants were included in future studies. However, future studies need to do more than just validate the trends found by the present study, using a larger numbers of participants. Future studies need to also discover the relationships that may exist for participants outside of the narrow ranges of participant inclusion criteria in the present study. This would allow clinicians to use research findings regarding AVI relationships to hearing aid outcomes to assist with

the selection of interventions for all of their clients, regardless of age and hearing impairment degree, type, and configuration.

4.8.4 Visual acuity effect on auditory-visual integration

Unlike many published studies into AVI, the present study did not screen participants for visual acuity. The participant group included a wide range of visual acuity scores. These scores were used as potential covariate controls but no statistically significant relationships were found related to visual acuity. A future study should enrol participants known to have a wide range of visual acuity scores from normal vision to near blindness. This would allow the relationship between visual acuity and the UCAMST-measured AVE and visual-alone test scores, to be determined. A lower limit on poor visual acuity might be found below which the benefits of visual information while listening to speech-in-noise may no longer apply.

4.8.5 UCAMST vs QuickSIN for diverse demographic groups

As discussed above in section 4.6, the results of the present study suggest that the UCAMST may be able to replace the QuickSIN test. To confirm this would require a future study to compare UCAMST and QuickSIN test results for more heterogeneous populations of participants.

A future study should enrol a larger number of participants with varying degrees, types, and configurations of hearing impairment to see if the present study's correlation found between UCAMST SNR_20% and SNR loss measured by the QuickSIN test still holds for these other types of hearing impairment. This future study should be separate to other future studies relating hearing aid outcomes to AVE. A separate study would be free from the participant inclusion criteria of a hearing aid outcomes study. The goal of the separate future study should be to produce a transfer function from SNR_20% results to estimated QuickSIN test result equivalents. This would allow SNR_20%

results to be transformed into estimated QuickSIN test results. SNR_20% results could then be used for the purposes for which the QuickSIN test has previously been used. An example of a purported existing purpose for QuickSIN test is to assist in determining the need for directional microphones and remote microphones (Etymotic Research, 2006).

4.9 Conclusion

The present study began with the research question "Is auditory-visual integration ability in older adults related to hearing aid outcomes?". The main finding of the study was that the AVE predictor variable was related to the IOI-HA-Average hearing aid outcome variable with a correlation of $r_s = 0.440$ and a significance of $p = 0.175$. The relationship was not statistically significant, but along with other supporting relationships that agree with findings in literature, the author's opinion is that further studies into AVI and hearing aid outcomes are warranted.

If the population correlation was the same as the present study's sample group of participants correlation of $r_s = 0.440$, then the effect size would be $r^2 = 0.194$. This would suggest that 19.4% of the variation in the hearing aid outcome variable IOI-HA-Average could be accounted for by variations in the predictor variable AVE.

While the present study's results were statistically inconclusive, many observations have been made during this first study into the research question and this can help guide future studies. AVE appears to be a promising predictor of hearing aid outcomes based on the results of the present study. If future larger studies can show statistically significant results, then the use of auditory-visual test tools by practising audiologists could become routine. Such routine use could be an input to designing maximally effective rehabilitation strategies, including: hearing aids, eye glasses, auditory-visual training, auditory-alone training, and language training.

Another objective of the present study was to measure participant SNR loss to help determine if the UCAMST could potentially replace the QuickSIN test in routine clinical test protocols. The results of the present study suggest that the UCAMST may be able to replace the need for QuickSIN testing. To confirm this would require a future study to compare UCAMST results with QuickSIN test results for other populations of participants.

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APPENDIX 1 Participant invitation materials

Appendix 1.1 Study flyer

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Seeking Participants

Auditory-visual speech reading and hearing aids

Many things can impact on the benefit people get from hearing aids when listening to speech in background noise. One of these things is the ability to listen to speech and lip read at the same time (together called speech reading). There has been no research that measured how a person's speech reading skill is related to the benefit they get from hearing aids. Everyone speech reads but some are better at it than others.

Information from this research may help to improve clinical practice in the area of selecting hearing rehabilitation strategies for the hearing impaired, including candidacy for hearing aids.

What you get

- Free testing of your speechreading ability in noise
- Test results may inform your clinician about how to improve your hearing rehabilitation
- A petrol voucher to cover cost of any additional travel
- Confidentiality & anonymity

What you do

- Return the postage paid envelope after filling in the enclosed letter of interest
- Read an information sheet and later sign a consent form if you are happy to participate
- Attend a speechreading test to repeat sentences heard while watching a face and lips on a screen
- Have your eye sight tested
- Fill in some questionnaires
- The total time it will take you is less than two hours

Who is it for

- Anyone aged 60 and above
- Both men and women
- People who have had a hearing aid for 6 months or more

Appendix 1.2 Letter of interest

Letter of Interest for study: Is auditory-visual integration a factor in hearing aid outcomes?

Return this letter using the provided envelope
Or ring us on: 03 xxx xxxx ext. xxxx
Or email us at: xxxxxxx@canterbury.ac.nz

Dear researchers,
I would like to take part in this study. Please contact me to arrange an appointment.

My name is (please print): _____

My postal address is: _____

_____

_____

_____

My phone number is: Land line _____ Mobile _____

My e-mail address is: _____

Return this letter using the pre-paid return envelope that is already addressed to:

Greg O'Beirne
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch 8140

Appendix 1.3 Participant information sheet

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Communications Disorders Department
Private Bag 4800
Christchurch 8140
New Zealand
Telephone: 03 - xxx xxxx ext. xxxx
Email: xxxxxx@canterbury.ac.nz

17 June 2015

Is auditory-visual integration a factor in hearing aid outcomes?

Information Sheet for Participants

I, Eric Andre, am a Master of Audiology student from the University of Canterbury (UC) and I am currently undertaking a thesis project as a requirement of the Master degree. When we listen to someone speak in a noisy environment, our ability to understand them is usually improved if we can clearly see their face. This is known as "speech reading" or auditory-visual integration, and some people are better at this than others. The purpose of my project is to examine whether people with better auditory-visual integration ability in background noise have better outcomes with their hearing aids. We have developed a new test which examines this ability, and it is hoped that the findings of this study will discover ways in which this test can be used in clinical settings to help in decisions around which hearing rehabilitation strategies are right for different individuals.

In addition to assisting the broader community, participants in this study may benefit personally by having in-depth knowledge provided to their clinician about their auditory-visual integration abilities and their experiences with their hearing aid, which may allow their clinician to further fine tune their rehabilitation.

This project is kindly supported by <private clinic> and the University of Canterbury hearing clinic, who are allowing us to invite clients who are eligible to take part in the study. We would like to invite you to participate in this study.

It is entirely your own decision to participate in this study. A letter of interest is enclosed along with

this Information sheet. Please return the letter of interest in the enclosed postage paid envelope if you are interested in participating in this study. A consent form will be available for you to sign during a face to face meeting if you agree to participate in this study. There is little risk associated with participating in this study, apart from the possibility of feelings of embarrassment regarding your speech intelligibility performance scores and scores from the cognitive (mental skills) ability test. A list of available support services is provided at the end of this document.

If you kindly agree to participate in this study , your involvement in this project would be one testing appointment soon after your decision to participate in this research. The appointment would involve.

1 A vision test
2 Word recognition tests listening to sentences in noise. Sometimes this will be with sound only, sometimes with sound and the moving face and lips of a talker on a screen, and sometimes without sound and only the moving face and lips of the talker on a screen. Questionnaires regarding your experiences listening to speech with and without hearing aids in everyday life.
3 A cognitive (mental skills) test involving following verbal instructions to solve problems using a pencil on a piece of paper showing some diagrams.
4 A questionnaire regarding your hearing and health history.

Your total appointment time will be less than two hours.

Testing will take place in a private room at the University of Canterbury. You are encouraged to bring family members and/or friends to research testing appointments if you wish.

Additionally, I would like your permission to acquire the following information in your clinic file from your clinician:

1 Hearing test results
2 Hearing aid brand/model/style
3 Information about how your hearing aid was set up and adjusted by your clinician.
4 The technology features available in your hearing aid and which of those were enabled

Participation is voluntary and you have the right to withdraw at any stage during the research without penalty; withdrawal will not in any way affect the treatment or services offered to you by your clinician . If you withdraw, I will remove information relating to you up until my results are statistically analysed, at which point data removal becomes impossible. Therefore, you are able to withdraw up until 14 November 2015.

The research will be published in a Masters thesis. A thesis is a public document and will be available through the UC Library. The utmost care will be taken to ensure your confidentiality is maintained. No names, initials, or other personally identifying information will be included in the

thesis. The results of the project may be published in publicly available scientific journals and seminars, but again you may be assured of the complete confidentiality of data gathered in this investigation. Hearing clinics will follow their usual procedures for recording/storing client information. Only my supervisors and I will have access to the obtained data, and this data will be stored in a secure, locked room for five years at which point it will be destroyed. If you would like a copy of the project results, please tick the appropriate box on the consent form. If you would like me to share your test results with your Hearing clinician, please tick the appropriate box on the consent form. Sharing your test results with your clinician may allow further fine tuning of your hearing rehabilitation.

This project is being carried out as a requirement for the Master of Audiology programme by me, Eric Andre (xxxxx@pg.canterbury.ac.nz 03 xxx xxxx), under the supervision of Assoc. Prof. Greg O'Beirne and Dr Rebecca Kelly. If you have any questions about participation in the project, please contact Assoc. Prof. Greg O'Beirne at xxxxxx@canterbury.ac.nz 03 xxx xxxx ext. xxxx, or Dr Rebecca Kelly-Campbell at xxxxx@canterbury.ac.nz 03 xxx xxxx ext. xxxx. They will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

We sincerely thank you for taking the time to consider being involved in this project. . Please return the letter of interest in the enclosed postage paid envelope if you are interested in participating in this study.

Eric Andre

Available support services:

LifeLine
09 5222999 (within Auckland)
0800 543 345 (outside Auckland)
http://www.lifeline.org.nz/

New Zealand Association of Counsellors
http://nzac.org.nz/nzac_counsellor_search.cfm
07 834 0220 (National Office)

Appendix 1.4 Participant consent form

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Communications Disorders Department
Private Bag 4800
Christchurch 8140
New Zealand
Telephone: 03 - xxx xxxx ext. xxxx
Email: xxxxxxx@canterbury.ac.nz

For researcher's use only:
Client ID number:……

Is auditory-visual integration a factor in hearing aid outcomes?

Participant consent form

I, ……....., have been given a full explanation of this project, have had the opportunity to ask questions, and have been provided with enough time to consider my consent for this project.

I understand what is required of me in agreeing to take part in this research. I understand that some clinical information (my hearing test results and hearing aid information) will be handed on to the researcher by my clinician. I understand that all forwarded information will be kept confidential by the researcher.

I understand that participation is voluntary and I may withdraw at any time during the study without penalty and without affecting my future audiological care. Any information I have provided can be withdrawn up until 14 November 2015, at which point the results will be statistically analysed and data removal becomes impossible.

I understand that any information or opinions I provide will be kept confidential to the researcher and the project supervisors and that any published or reported results will not identify the participants.

I understand that a thesis is a public document and will be available through the University of Canterbury Library. I understand that the information in the thesis may also be published in publicly available scientific journals and scientific seminars.

I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form and will be destroyed after five years.

I understand the risks associated with taking part and how they will be managed.

I understand that I can contact the researcher, Eric Andre xxxxx@pg.canterbury.ac.nz, or supervisor, Dr Gregory O'Beirne (at xxxxxx@canterbury.ac.nz 03 - xxx xxxx ext. xxxx) Dr Rebecca Kelly (at xxxxxx@canterbury.ac.nz 03 - xxx xxxx ext. xxxx) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)

☐ I agree to the transferral of clinical information to the researchers.

☐ I agree to the transfer of test and questionnaire research results to my clinician.

☐ I wish to receive a report summarizing the findings of this project.
Please select a method for sending you a copy of the report and provide the appropriate address:

☐ *Email:……*

☐ *Post:……*

By signing below, I agree to participate in this research project.

Name:

Date:

Signature……

Please return this form to the researcher

We sincerely thank you for taking the time to be involved in this project.
Eric Andre, Master of Audiology student from the University of Canterbury

APPENDIX 2 Test appointment materials

Appendix 2.1 Results sheet

Participant Test Procedure for AV Integration Study

Participant name / number:

Phone numbers:

Test Date:

Test time:

Before Going to the Test Room

- Prepare participant envelope with forms and test sheets
- Write participant phone numbers, NAL2 loudness, Pure tone average
- Bring petrol voucher
- Bring: Eye chart lamp, reading span cards, spare +3 reading glasses
- Get Otoscope
- Prepare test room and booth room

1. Provide a consent form for the participant to read. The participant has previously sent back an expression of interest form. The consent form has more details (detail also covered by the Study Information Sheet in the invitation envelope) that can be discussed with the student. The participant may choose to sign the consent form, or not sign the consent form and either withdraw from the study or make a new appointment to have time to consider the form.

Consent signed (Y/N):
Withdrawn (Y/N):
New Test date:
Store consent in participant envelope (tick): ___

2. Assess native English speaker status. Check for wax.

Native speaker? (Y/N):
Occluding wax? (Y/N) Right: Left:

3. Administer a vision test using a Snellen eye chart at a distance of 20 feet.

Check: Participant cannot see chart during set up; chart on lit wall; mark 20 feet line.
If normally worn, wear eye glasses used for walking/driving/visiting friends.

Visual Acuity (circle): 20/20 20/30 20/40 20/60 Worse

4. Loudness level

Pure tone average: Right: ____ Left: ____

NAL2 recommended: Right 65 + ____ = ____ dB Left 65 + ____ = ____ dB

Use AV tester speech without noise for...

NAL2 comfortable?: Right ____ Left ____

NAL2 audible?: Right ____ - 15 = ____ dB OK? __ Left ____ - 15 = ____ dB OK? __

Level for AV test: Right ____ dB Left ____ dB

Loud but OK level for QuickSIN test: Right ____ dB Left ____ dB Both ____ dB

Two extra practice sentences at “level for AV test” (tick): ___

Demonstrate masking noise in each ear (tick): ____

5. Use the University of Canterbury Auditory-visual Matrix Sentence tester

Seat the participant 1.1 metres from the computer screen.
If normally worn, wear eye glasses used for walking/driving/visiting friends.

Audio only settings: Binaural, constant noise, 2Track20/80Pair, SNR, NZEngMatrix, open set, this screen, auditory alone

AV settings: Binaural, constant noise, Fixed dual, SNR, NZEngMatrix, open set, Pop out, auditory visual

Visual only settings: Binaural, constant noise, Fixed dual, SNR, NZEngMatrix, open set, Pop out, visual alone

A) The signal to noise ratio (SNR) in the audio only condition that results in 20% correct.

SNR for 20% correct: ____

B) The signal to noise ratio (SNR) in the audio only condition that results in 80% correct.

SNR for 80% correct: ____

C) Using the SNR from "A", measure the percentage correct in the auditory-visual condition, and calculated the degree of auditory-visual enhancement.

AV percent correct: ____

AV enhancement = (AV – A) / (1 – A) = (- 0.2) / (1 - 0.2) =

D) Using the SNR from "B", measure the percentage correct in the auditory-visual condition, and calculated the degree of auditory-visual enhancement.

AV percent correct: ____

AV enhancement = (AV – A) / (1 – A) = (- 0.8) / (1 - 0.8) =

E) Measure the percent correct in the visual only condition (no sound).

Vision-only percent correct: ____

6. Administer the International Outcome Inventory for Hearing Aids (IOI-HA) in an interview format. There are eight questions on a five item scale.

Put participant name and date on IOI-HA form (tick):

Store IOI-HA in participant envelope (tick):

7. Administer the Reading Span Test to measure working memory.
Hand out reading span test instructions.
Sit participant to my right. Turn cards for participant.
Use results sheet on my left during test with answers hidden under the fold.

Span size with three sets wrong:

Longest span with two or more of three sets correct:

8. Administer the study specific questionnaire.

Put participant name and date on the questionnaire (tick):

Store questionnaire in participant envelope (tick):

9. Administer the Montreal Cognitive Assessment – MoCA questionnaire in an interview format.

MoCA score raw: (out of 30)

Add one if no tertiary education:

MoCA adjusted score:

MocA result (Circle): Normal (>=26) Abnormal (<26)

If abnormal, give a letter. The letter recommends seeing their general practitioner doctor for further evaluation.

10. Administer the QuickSIN test.
Instruct on how do the QuickSIN. Present one practice list and two test lists.

SNR loss 1: dB

SNR loss 2: dB

Average SNR loss: dB

11. Sign for petrol voucher

Petrol Voucher signed for (tick): ____

Collect the following from the client file:

1. Audiogram (tick):

2. Hearing aid Brand:

   Model:

   Style:

3. Amplification prescription (e.g. NAL NL2):

4. Real Ear Measure (REM) performed (Y/N/?):

5. The technology features available in the hearing aid, and which of those were enabled:

6. Hearing aid setting information (e.g. acclimatisation percentage, etc.):

Appendix 2.2 Auditory-visual test instructions

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Communications Disorders Department
Private Bag 4800
Christchurch 8140
New Zealand
Telephone: 03 - xxx xxxx ext. xxxx
Email: xxxxxxx@canterbury.ac.nz

Is auditory-visual integration a factor in hearing aid outcomes?

Auditory-Visual Test Instructions

The auditory-visual test measures how much your speech understanding improves when you can see the face of the person talking. Relax and sit still looking towards the screen. You will hear voices sometimes with the talker visible on the screen and sometimes not visible. At the end of each sentence, just repeat back the sentence you heard to the student researcher. If you are not sure, just guess what you think you might of heard. For one test you will see a talking face on the screen but no sound at all. See if you can lip read what was said.

You don't need to remember the above written instructions. The student researcher will give you instructions before the test begins. Feel free to ask questions. The student will also prompt you for the next step throughout the test.

Appendix 2.3 Reading span test instructions

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Communications Disorders Department
Private Bag 4800
Christchurch 8140
New Zealand
Telephone: 03 - xxx xxxx ext. xxxx
Email: xxxxx@canterbury.ac.nz

Is auditory-visual integration a factor in hearing aid outcomes?

Participant Reading Span Test Instructions

The "reading span test" is being used to measure your "working memory". Working memory is known to affect people's ability to recognise words in noise.

Below are some example sentences used to measure your reading span. You will read the sentence on each card aloud. After two cards you will see a blank card. When you see the blank card, you will say out loud the last word you remember from each sentence in order. You will do this three times so that you see three sets of two sentences each followed by a blank card. After that, the next three sets of sentences will have three sentences between blank cards, then four sentences between blank cards, and so on until there are six sentences between blank cards.

You will start with by practising using three sets of two cards. After the practice, the scored test will then begin. You will finish testing when you get all three sets of sentence last words wrong. Your reading span score is the number of sentences between blank cards for the last group of three sets where you got at least two out the three sets correct

You don't need to remember the above written instructions. The student researcher will give you instructions before the test begins. Feel free to ask questions. The student will also prompt you for the next step throughout the test.

These are two example sentences that would be printed, each on a separate card:

"Two or three substantial pieces of wood smouldered on the hearth, for the night was cold"

"There was still more than an hour before breakfast, and the house was silent and asleep"

Appendix 2.4 Study questionnaire

Communications Disorders Department
Private Bag 4800
Christchurch 8140
New Zealand
Telephone: 03 - xxx xxxx ext. xxxx
Email: xxxxxxx@canterbury.ac.nz

Is auditory-visual integration a factor in hearing aid outcomes?

Participant questionnaire

Your Name: .....

Today's date: .....

1. On average, how many hours a day do you use your hearing aid? ….....

2. What age were you when your hearing loss began? ….....

3. Have you had a stroke? Yes / No When? ….....

4. Have you had a concussion? Yes / No When? ….....

5. Have you had a head injury? Yes / No When? ….....

6. Have you had any brain disorders? Yes / No When? .....

Type of disorder: ….....

Appendix 2.5 MoCA referral letter

Date:

Dear:

Re: Cognitive screening assessment as part of the research project "Is auditory-visual integration a factor in hearing aid outcomes".

Thank you for participating in the research project "Is auditory-visual integration a factor in hearing aid outcomes". As part of this research, you completed an assessment called the Montreal Cognitive Assessment (MoCA). This is a quick screening assessment of thinking and memory. A screening assessment is used to identify whether people *might* have a problem in a certain area. It does not determine whether a problem exists.

Your score on the MoCA was outside of what we would generally expect, which suggests there might be a problem. We suggest that you follow up with your GP. We will give you your MoCA results along with this letter, so that you may discuss this further with your GP.

If you require further clarification, please do not hesitate to contact me. Thank you again for participating in our research.

Regards,

Eric Andre

Master of Audiology student
Department of Communication Disorders
University of Canterbury
Email: xxx@xxx.ac.nz
Phone: xx xxx xxx

APPENDIX 3 Human ethics committee approval

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2015/51

8 July 2015

Eric Andre
Department of Communication Disorders
UNIVERSITY OF CANTERBURY

Dear Eric

The Human Ethics Committee advises that your research proposal "Is auditory-visual integration a factor in hearing aid outcomes?" has been considered and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 7 July 2015.

Best wishes for your project.

Yours sincerely

Lindsey MacDonald
Chair
University of Canterbury Human Ethics Committee