Assessment of the reliability of a simplified matrix sentence test in noise

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Thank you to all the people that gave up their time to voluntarily participate in this research study.

Abstract

The current study aimed to evaluate the reliability of a simplified matrix sentence test in assessing older hearing-impaired adults who may also have some mild cognitive impairment in their perception of speech in noise. The simplified matrix sentence test, known as the simplified University of Canterbury Auditory Matrix Sentence Test-Paediatric (UCAMST-P) is a shorter and less cognitively demanding test that was originally designed to test paediatric listeners. We hypothesise that the shorter and simpler format of the test may make it more suitable for testing older hearing-impaired subjects that may also have cognitive impairment. A large cohort of 64 adults that were recruited through the University of Canterbury speech and hearing clinic were tested with the simplified UCAMST to determining their speech recognition threshold (SRT) in noise. Additionally, their speech recognition in noise was assessed with a clinically available test, the Quick speech in noise (QuickSIN™) test for comparison studies. Participants pure tone hearing thresholds and cognitive status were also assessed. Results showed that the simplified UCAMST gave consistent and reliable results over two trials. When different response formats were used in the simplified UCAMST, open-set and closed-set, it was found that the open-set was more reliable and had a smaller measurement error compared to the closed-set response condition. However, the participants attained better SRTs in the closed-set condition over the open-set condition. It is hypothesised this is due the cognitive advantage of being able to see the word matrix in the closed-set condition which is less cognitively demanding and offers visual cues to the possible word presented when speech intelligibility may not be optimal. Overall, it was found that the two different response conditions could not be used interchangeably. The reliability of the simplified UCAMST was found to be robust against the effect of increasing hearing loss, age and cognitive status of the listener in the closed-set condition. The largest effect found was the effect of older age and mild cognitive impairment on the measurement error in the open-set response condition. The results from the simplified UCAMST positively correlated with the results from the currently clinically used QuickSIN™ test proving the validity of the simplified UCAMST. Moreover, the SRTs derived from the simplified UCAMST had a lower measurement error compared to those found with the QuickSIN™. This study provides important evidence that the simplified UCASMT is a valid, reliable and accurate test for assessing the performance in speech in noise of older adults with a hearing impairment.

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List of abbreviations

ABG	Air-Bone Gap
ASHA	American Speech-Language-Hearing Association
BKB-SIN	Bamford-Kowal-Bench speech-in-noise
dB	Decibels
dB HL	Decibels Hearing Level
dB SNR	Decibels Signal-to-Noise Ratio
dB SPL	Decibels Sound Pressure Level
CVC	Consonant-Vowel-Consonant
HA	Hearing Aid
HI	Hearing Impairment
HINT	Hearing in Noise Test
Hz	Hertz
IHCs	Inner Hair Cells
LE	Left Ear
Mini-ACE	Mini-Addenbrooke's Cognitive Examination
MST	Matrix Sentence Test
NH	Normal Hearing
NZAS	New Zealand Audiological Society
OHCs	Outer Hair Cells

PB_{max}	Presentation level at which maximal performance is achieved
PI	Performance-Intensity
PTA	Pure-Tone Average
RE	Right Ear
SD	Standard Deviation
SNHI	Sensorineural Hearing Impairment
SNR	Signal-to-Noise Ratio
SPIN	Speech Perception in Noise
SRT	Speech Recognition Threshold
UCAMST	University of Canterbury Auditory-Visual Matrix Sentence Test
UCAMST-P	University of Canterbury Auditory-Visual Matrix Sentence Test – Paediatric. **Note: In this thesis the UCAMST-P will be referred to as the simplified UCAMST test.**
WHO	World Health Organisation

Chapter 1: Introduction

1.1 Introduction to hearing loss

The World Health Organisation (WHO) has referred to hearing loss as a "silent epidemic" with 350 million people worldwide affected and the consequences of their hearing loss being frequently underestimated (Olusanya et al. 2014; WHO, 2017). Within the next decade, the number of people affected by hearing loss is expected to increase to 630 million with the burden of hearing loss on the global economy estimated to be US$750 billion per year (WHO, 2017). The consequences of hearing loss in adults include feelings of social isolation and depression (Arlinger, 2003) and there is increasing evidence of a correlation in older adults, between hearing loss and a decrease in cognitive function (Lin , 2011, 2013).

1.2 Types of hearing loss

There are three main types of hearing loss, defined by the part of the auditory system where that pathology is located that has caused the hearing loss. If the pathology is in the outer or the middle ear sound cannot be conducted to the organ of hearing, the cochlea. Hence this type of hearing loss is called a conductive loss. If damage has occurred to the cochlear itself, or further up the auditory nerve pathway, this is known as a sensorineural hearing loss. The third type of hearing loss is a mixed loss and is caused by a combination of both conductive and sensorineural hearing loss.

Sensorineural hearing loss is the most common form of hearing loss as damage to the sensory cells and metabolic processes in the cochlea occurs through the aging process. This type of hearing loss is known as presbycusis and affects 40 percent of adults over the age of 65 (Gates & Mills, 2005). Apart from reduced hearing sensitivity, presbycusis is characterised by slower central processing of sound, impaired localisation of sound sources and a reduction in frequency discrimination which leads to an impaired ability to discriminate speech in background noise (Moore, 2008). The loss of hearing sensitivity begins in the higher frequencies which makes it difficult to perceive speech in noisy or reverberant environments. When the hearing loss progresses to affect the 2000-4000 Hz range speech understanding is also reduced in quiet environments. This is because the ability to hear the voiceless consonants is compromised (/f/, /k/, /p/, /t/, /s/ and /ch/) (Gates & Mills, 2005).

Overall, individuals with a hearing loss perceive a speech signal that is less audible and more distorted and the effect of both is magnified in the presence of background noise.

1.3 Assessing hearing loss

1.3.1 Pure tone audiometry

The degree and type of hearing loss can be determined through different audiological assessments, with the fundamental assessment being pure tone audiometry. Pure tone audiometry is a subjective assessment that determines an individual's degree of hearing loss by finding their hearing thresholds. A behavioural response elicited by pure tones presented at different intensity levels and frequencies is graphed on an audiogram. The behavioural response can be a button press, raising of the hand, tap on a table or some other indication that the subject has heard the tone being presented to them. Pure tones of different frequencies are systematically presented at different intensity levels until the quietest intensity the subject can hear the tone 50% of the time has been established (Carhart & Jerger, 1959; NZAS, 2020). This is plotted as the subject's hearing threshold (in dB HL, decibels hearing level) for the frequency being tested on the audiogram (Valente, 2009). The frequencies tested are the octave frequencies between 250 and 8000 Hz (Hertz) as these are the most important frequencies for understanding speech (Schlauch & Nelson, 2009). The completed audiogram provides a graphical representation of the hearing sensitivity (dB HL) as a function of frequency (Hz), and the configuration, severity, and type of loss, can be ascertained for the subject (NZAS, 2020; Schlauch & Nelson, 2009).

1.3.2 Limitations of pure tone audiometry

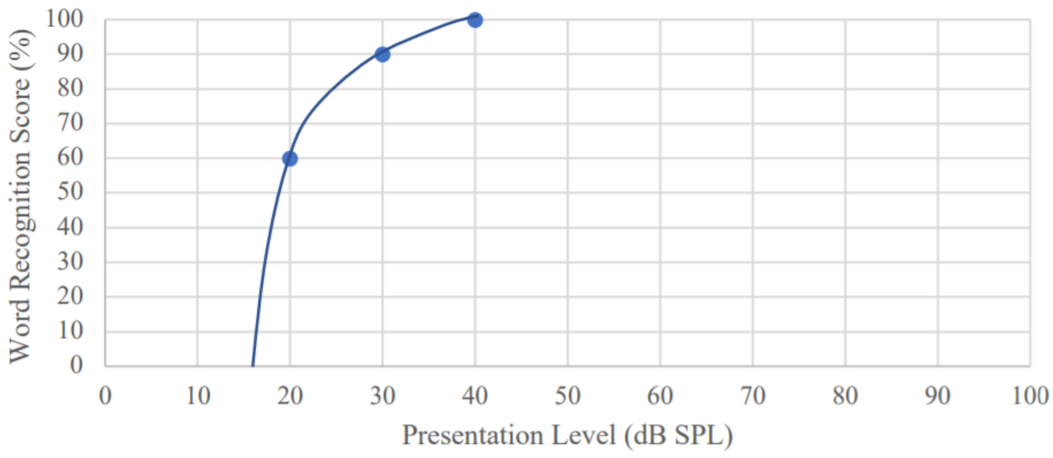
One of the limitations of pure tone audiometry is its inability to predict speech in noise (SiN) perception, and therefore everyday listening ability (Heinrich et al., 2015; Holmes & Griffiths, 2019; Killion, 2002; Middelweerd et al., 1990; Vermiglio et al., 2012). Individuals that report having difficulty understanding SiN often show normal pure tone thresholds (Hind et al., 2011). Considering these limitations speech tests that involve understanding sentences in noise are a much better predictor of everyday difficulties of understanding SiN (Heinrich et al., 2015, 2016; Lunner & Sundewall-Thoren, 2007).

1.4 Speech testing

Speech testing is an essential element in the audiological test battery as it assesses the ability to understand speech, thus providing information related to the communication difficulties people with hearing loss face (Hamid & Brookler, 2006). Tests using speech stimuli also provide further diagnostic information to the nature of the hearing loss and act as a cross-check of the reliability of the pure tone thresholds (Jerger & Hayes, 1977). Scores on speech tests are an important aid to guide clinicians on an individual's candidacy for cochlear implants, hearing aids, and assistive listening devices (Hoppe et al., 2015). Normally, speech testing involves a listening and a response part; participants listen to a speech snippet, which can be phonemes, words, or whole sentences and, either repeat what they heard (“open-set” response mode) or select from a number of options ("closed-set" response mode). The tests take place in quiet or in noise at different signal-to-noise ratios (SNRs).

1.4.1 Speech in Quiet Testing

Speech recognition and intelligibility can be assessed by speech-in-quiet testing in the audiology clinic. In New Zealand, the current audiological practice is to administer a speech test in quiet conditions using the meaningful Consonant-Vowel-Consonant (CVC) word lists (Boothroyd, 1968; Boothroyd & Nittrouer, 1988; NZAS, 2016; Purdy et al., 2000). The word lists are made up of ten monosyllabic and phonetically balanced words and are presented without context following the carrier phrase "say". After each word is presented, the subject is required to repeat the word aloud. If the subject does not recognise the word they are encouraged to say any sound(s) they may have recognised. This is important as the test is scored based on the phonemes correctly identified, with each word having three identifying phonemes (Boothroyd, 2008). Words lists are presented to the subject at different intensity levels (dB HL), at an intensity where they are expected to get 97-100% of the words correct, an intensity where they get approx. 50% of the words correct, and a third intensity where they get less than 50% of the words correct. These three scores (percentages correct) are plotted on a graph against their presentation intensity level (dB HL) and a line of best fit is drawn between the points. This plot is known as a performance intensity (PI) function, and from this the SRT (the speech reception threshold), or the level correlating to 50% intelligibility, can be derived (Boothroyd, 2008; Brand & Kollmeier, 2002). An example of a PI function is shown in Figure 1.



Note: PImax = presentation intensity at which maximal performance is attained. SRT= speech recognition threshold, intensity level at which the subject scores 50% of their PI max.

Figure 1:An example of a PI function derived from the CVC speech test

CVC Speech testing in quiet is useful as it provides a cross check for the hearing thresholds ascertained by pure tone audiometry. The subject's speech recognition score should be consistent (within 15 dB) with their pure tone threshold at 1000 Hz (Boothroyd, 1968; Boothroyd, 2008). Additionally, the shape of the PI function and its comparison with a normative range for PI functions is a useful counselling tool. However, speech in quiet tests have many limitations that argue against using them as the only measure of speech recognition in clinical practice, which is the case in New Zealand.

1.4.2 Limitations of speech in quiet testing

The most obvious limitation of speech testing in quiet is that everyday communication is not conducted in the absence of background noise. The most common complaint from individuals with a hearing loss is the difficulty they experience in understanding speech in the presence of background noise (Beattie et al., 1997; Dirks et al., 1982; Hochmuth et al., 2012).

Consequently, speech testing in quiet does not give a realistic representation of a person's ability to hear speech in noisy everyday situations, and a person's difficulty in understanding speech in a noisy environment can be much more severe than what would be expected based on their audiogram (Smoorenburg, 1992).

Additionally, the speech in quiet test, CVC words, that is currently used in New Zealand does not have the sensitivity to distinguish between normal hearing subjects from those with a mild hearing loss. This is because the test suffers from a ceiling effect as normal hearing listeners and those with a mild hearing loss often score 100% and any further improvement cannot be recognised (Beattie et al., 1997). The test is also vulnerable to floor effects where scores of close to 0% are frequently obtained for groups of listeners with differing severities of hearing loss, this makes it impossible to identify meaningful differences in speech recognition abilities for some groups of listeners (Gifford et al., 2008).

1.4.3 Speech in noise testing

The importance of speech in noise testing has been recognised since the 1970s when it was recommended that such tests should be included in the standard audiological test battery (Carhart & Tillman, 1970). The pure-tone audiogram is not a good reflection of the difficulty understanding speech in noise that an individual may have (Plomp, 1978; Smoorenburg, 1992). The pure-tone audiogram and speech audiometry in quiet assesses the loss of hearing sensitivity, but do not assess listening abilities at supra-threshold sound pressure levels that make communication in noisy environments difficult (Sanchez-Lopez et al., 2021). Hearing and understanding speech in noise is the most difficult listening task for a person with a hearing loss (Healy & Yoho, 2016). This is because of several physiological factors in addition to their elevated thresholds, these being loss of frequency selectivity and temporal resolution, and the presence of loudness recruitment (Legris et al., 2018; Peters & Moore, 1992). Speech audiometry assesses both the loss of a listener's sensitivity for speech, the audibility and distortion component of hearing loss, as well as the loss of clarity of speech (Plomp, 1978).

Speech in noise tests should be used to assess people with hearing loss but also people with normal peripheral hearing who have difficulties hearing in noisy environments, to diagnose pathologies, such as auditory neuropathy and auditory processing disorders (Iliadou, et al., 2017; Wilson et al., 2007; Zeng & Liu, 2006). However, speech in noise tests are often omitted from the standard adult audiological test battery (Ross et al., 2021; Spyridakou & Bamiou, 2015).

1.4.4 Types of noise used in speech tests

Different types of background noise can be used in speech in noise tests which acts as an acoustic masker to the speech signal. The most common types of noise used are steady state speech spectrum/constant speech-shaped noise and multi-talker babble noise. Both types of noise have advantages and disadvantages. Generally, the greater the acoustic dissimilarity between the speech stimuli and the competing masker noise, the easier it is to perceptually segregate them (Brungart et al., 2001; Durlach et al., 2003). For this reason, it is easier to segregate a speech signal from steady state constant noise (despite its identical spectrum) compared to multi-talker babble noise (Ben-David et al., 2012).

Speech babble noise is used in the QuickSIN™. The advantage of this type of noise is that it is more like real-world background noise and has more face-validity for use in a clinical setting, however it produces less reliable test results compared to the use of constant speech shaped noise (Killion et al., 2004; Stone, 2016). Speech shaped noise has greater sensitivity as it has very similar spectral content to the speech stimulus (Francart et al., 2011; Wagener & Brand, 2005). For this reason, constant speech noise is often used for research projects to discriminate between two variables (Nilsson et al., 1994; Plomp & Mimpen, 1979; Wagener & Brand, 2005) and was used in this research project for the matrix sentence testing.

1.5 SRT and Psychometric Functions:

When speech testing is conducted in noise the subject's performance is represented as a percentage of words detected correctly as a function of the SNR (MacPherson & Akeroyd, 2014). This is illustrated as a psychometric intelligibility function which is sigmoid shaped and described by the threshold and the slope (Figure 2).

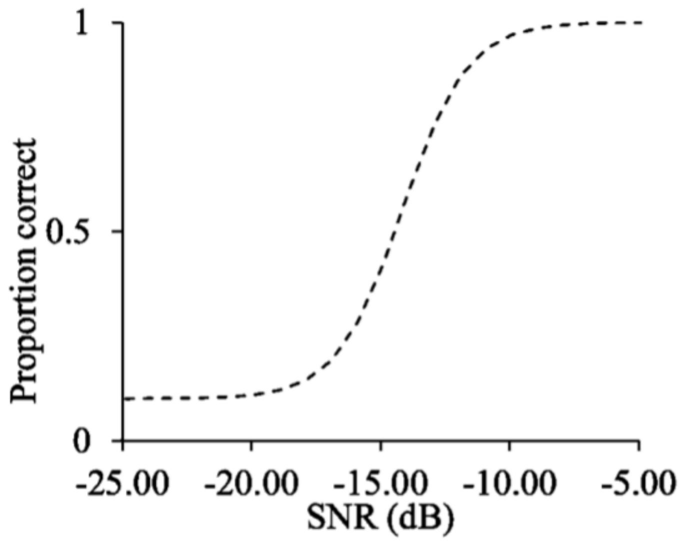


Figure 2:Example of a psychometric intelligibility function showing proportion of correct words detected as a function of the SNR (dB). A logistic psychometric function is fitted to the individual data points. Image from McClelland (2015, p.12).

The point on the psychometric function where the subject scores 50 percent intelligibility is their Speech Reception Threshold (SRT_{50}). The slope of the psychometric function at the location of the SRT determines how accurate the SRT is, as a strict inverse relationship. So, a steeper slope at the SRT means the SRT has a lower standard deviation (Ozimek et al., 2012). The slope of the psychometric function as a whole determines how sensitive the test is, as a strict positive relationship. So, a steeper psychometric slope means the test is more sensitive. Figure 3 illustrates two psychometric functions which differ in their sensitivities (steepness of slope). It can be seen by inference that larger changes to the measured intelligibility score can be attained by more minor adjustments in the level of the stimulus if a test is more sensitive (Brand & Kollmeier, 2002). This is an important clinical consideration as a more sensitive test means the SRT can be more accurately located in a shorter amount of time, with fewer trials (Francart et al., 2011). Additionally, greater benefits of slight adjustments to the SNR provided by amplification can be realised (Brand & Kollmeier, 2002; MacPherson & Akeroyd, 2014; Wilson et al., 2007).

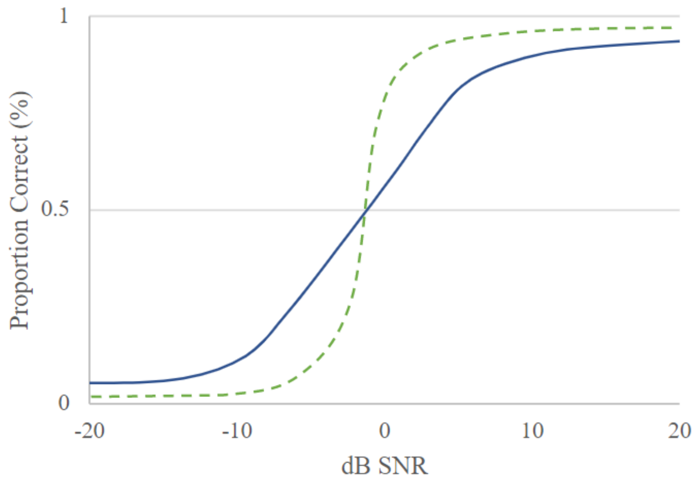


Figure 3: Example of psychometric functions with steep (green dashed line) and shallow (blue solid line) slopes. Image from Lay (2019, p. 15)

Using a signal to noise ratio to quantify performance in speech in noise is based on the fact that speech intelligibility depends on the intensity of speech relative to the masking level of noise, more than the absolute noise level (Hawkins & Stevens, 1950).

In the SNR model of speech in noise performance there are two critical factors for successful speech understanding, audibility and suprathreshold perceptual ability (Plomp, 1986). So, speech must be above an individual's hearing threshold to be audible. However, if an individual has a sensorineural hearing loss, they will have difficulties understanding speech beyond audibility. This is because the acuity of the auditory signal is degraded for them, and they require a higher SNR (Plomp & Mimpen, 1979). The SNR model of understanding speech in noise uses the SNR_{50} to account for effects of both audibility and suprathreshold factors and assumes that the speech intelligibility will be restored at an SNR that is higher than the threshold (Ross et al., 2021).

1.6 Types of SNR tracking measures used in speech tests

To estimate the SRT_{50}, speech tests can either use non-adaptive (fixed) or adaptive methodology. In non-adaptive speech tests the presentation intensity levels of speech are calculated before the test begins and do not change during the test, so the SNR is at a fixed level. In contrast, with adaptive tests the intensity level of the stimulus (either the speech or the noise) is varied based on the previous response, and therefore the SNR is variable (Levitt, 1971). Adaptive procedures can be split into three categories of procedures (Leek, 2001), PEST (parameter estimation by sequential testing), maximum-likelihood, and staircase (simple up-down) (Smits & Houtgast, 2006). The most common adaptive methodology used in speech in noise testing is the simple up-down procedure where the stimulus level is adjusted by a constant value either up or down depending on the preceding response until the intensity level is found at which the participants response is correct a specific percentage of the time (Brown, 1996; Brand & Kollmeier, 2002; Plomp & Mimpen, 1979).

1.6.1 A fixed speech in noise test

An example, of a fixed or non-adaptive speech in noise test is the Speech Perception in Noise test, known by the acronym SPIN (Kalikow et al., 1977). The SPIN test presents sentences at a chosen fixed SNR and the results are expressed as a percentage correct score. The disadvantage of fixed speech in noise tests is that they are highly susceptible to ceiling effects. In practice this means that once the subject scores 100% no further improvement can be shown. Fixed tests are also prone to floor effects where it can be difficult to ascertain what level the testing should start at to not make it too easy or too difficult. A fixed speech in noise test was not used in this study as they are not commonly used in the New Zealand clinical setting.

1.6.2 Adaptive speech in noise tests:

Examples of commercially available adaptive speech in noise tests are the Hearing in Noise Test (HINT) (Nilsson et al., 1994), and the Quick Speech in Noise test (QuickSIN™) (Killion et al., 2004) . For the HINT test protocol sentences are presented with speech – shaped masking noise at 65 dB SPL while the sentences are adjusted in 2 dB steps either up or down, depending on the previous response of the subject. Scoring of the test is based on the subject recalling all the key words in the sentence. The HINT is a truly adaptive test as the subject's response in the preceding trial dictates the presentation level of the sentence stimuli in the next trial (Levitt, 1971; Nilsson et al., 1994). In contrast, the QuickSIN™ is a pseudo-adaptive test as the subjects' responses do not dictate the presentation levels of subsequent trials. During the test the four-talker babble masking noise is varied so the SNR changes by 5 dB for the presentation of each new sentence, irrespective of what the subject scored for the preceding sentence. The speech stimuli presentation level remains fixed for the whole of the test (Killion et al., 2004; Taylor 2003). For both tests the final threshold of intelligibility is not expressed as a percentage correct score but instead expressed as an SNR. This avoids the problem of floor and ceiling effects that are common in non-adaptive speech tests (Gifford et al., 2008).

When a speech in noise test is used in New Zealand audiology clinics, it is most often the QuickSIN™ test used. For this reason, the QuickSIN™ was used in this study.

1.7 The Quick Speech in Noise Test (QuickSIN™)

The QuickSIN™ test (Killion et al., 2004) is a commercially available speech in noise test (Etymotic Research, IL) that comprises of lists of six sentences which are presented in multi-talker babble noise at different SNRs. Each sentence contains five keywords which are scored if the listener repeats them back correctly. The sentences used are phonetically balanced Harvard sentences (IEEE, 1969), constructed with proper syntax but lacking strong semantic cues. However, there are more contextual cues available to the listener compared with monosyllabic words.

The first sentence is presented at +25 dB SNR and each subsequent sentence is presented at a 5 dB lower SNR than the preceding one, until the sixth sentence is presented at 0 dB SNR. The results of the test are expressed as a SNR loss, which is defined as the increase in SNR (dB) necessary for a subject with a HL to receive speech-in-noise at levels comparable to a normal hearing subject at a specified performance level (usually 50%-word identification). Higher SNR loss scores represent a worse ability to understand speech in noise (Grant & Walden, 2013; Killion et al., 2004; Tayor, 2003).

1.8 Types of speech stimuli used in speech tests:

Speech tests can be based on scoring of single phonemes, words or whole sentences (Dietz et al., 2014; Wilson, 2005). Phoneme and word-based speech recognition tests can offer advantages over sentence-based tests as they take up less clinical time to administer and place fewer demands on the subject's auditory memory (Wilson et al., 2007). However, the use of word stimuli may give a less accurate estimate of a subjects' communication difficulties, compared to whole sentence-based tests (Hochmuth et al., 2012; Killion et al., 2004). Moreover, many studies have shown that sentence stimuli-based tests have steeper psychometric functions, and therefore more accurate measures of a subjects SRT, compared to single word-based tests (Bell & Wilson, 2001; Bosman & Smoorenburg, 1995; McArdle et al., 2005; Versfeld, et al., 2000). The main premise behind this is the fact that the more words that can be incorporated into a single trial, the greater the accuracy of the SRT measurements, and this is most efficiently achieved by using whole sentence stimuli rather than single words (Hagerman, 1979). Hagerman (1979) documented that the accuracy of a speech test is improved by $\sqrt{2}$ by doubling the number of words in a test.

Sentence stimuli have many other advantages over single word stimuli including representing a more realistic listening situation so providing a greater ability to assess a subject's ability to hear and understand speech in a real-world scenario (Dietz et al., 2014; Killion et al, 2004). This is due to the fact that sentence material represents a greater dynamic range reflecting the fluctuations, intonations, pauses, temporal elements and contextual cues present in every-day conversational speech (Nilsson et al., 1994). So, in conclusion sentence-based speech in noise tests afford a more realistic representation of a subject's communication difficulties in a real-life situation and this offers great rehabilitative information to the clinician (Ditz et al., 2014; Hagerman, 1982; Ozimek et al., 2009; Theunissen et al., 2009).

1.8.1 Sentence-based speech tests:

Speech tests that use sentence stimuli can be separated into two broad categories, ‘Plomp-type’ sentence tests (Nilsson et al., 1994; Plomp & Mimpen, 1979) and matrix sentence tests (MSTs) (Kollmeier et al., 2015). Plomp-type sentence tests are based on everyday meaningful speech and use phonetically and statistically equivalent sentences that have no consistent grammatical structure (Plomp & Mimpen, 1979). However, some contextual cues, including sematic, syntactic and prosodic, are available from neighbouring words, so some words could be extrapolated even if they were not heard correctly by the subject (Hutcherson et al., 1979). The use of neighbouring words can reduce the accuracy of speech recognition score as the listener can in some instances not hear the exact acoustic properties of the signal (Kalikow et al., 1977; Wilson et al., 2007). In comparison, sentence matrix tests have low sematic predictability. This means that there is very limited context information available from each word in the sentence to help predict other words in the sentence (Akeroyd et al., 2015; Kollmeier, 2015).

1.9 Matrix Sentence Tests:

The second category of speech tests that use sentence stimuli are the matrix sentence tests, of which the first was developed in the Swedish language by Hagerman (1982). Unlike the Plomp-type sentence tests, MSTs have a fixed grammatical structure, consisting of a name, verb, number, adjective, and object which are derived from a five by ten-word matrix (Kollmeier et al., 2015). The matrix can provide up to 10^5 (100,000) possible sentences that are syntactically correct but semantically unpredictable (Kollmeier et al., 2015; Meister, 2017). Since the development of the first MST in Swedish (Hagerman,1982), many more MSTs have been developed in other languages including German (Wagener et al., 1999), Danish (Wagener et al., 2003), British English (Hall, 2006), Polish (Ozimek et al., 2010), Spanish (Hochmuth et al., 2012), French (Jansen et al., 2012), Dutch (Houben et al., 2014), Finnish (Dietz et al., 2014), Italian (Puglisi et al., 2015), Russian (Warzybok et al., 2015a), Turkish (Zokoll et al., 2015), American English (Kollmeier et al. 2015), Malay (Jamaluddin, 2016), Australian English (Kelly et al., 2017), Indonesian (Primadita, 2017) and Mandarin (Hu et al., 2018).

Different language versions of MSTs have been developed as there is a significant reduction in speech intelligibility when listening to a non-native test speakers voice (Zokoll et al., 2013, Warzybok et al., 2015b). The test speakers' dialect, accent and pronunciation can negatively affect a subject's performance on the test, especially in the presence of an acoustic masker (Hochmuth et al., 2012, Wijngaarden et al., 2002; Zokoll et al., 2013).

1.9.1 Development of the University of Canterbury Auditory-Visual Matrix Sentence Test (UCAMST):

To address the limitations of using an international speech test in a New Zealand clinical setting with native New Zealand speakers, the University of Canterbury auditory-visual matrix sentence test (UCAMST) was developed by O’Beirne and Trounson (O’Beirne et al., 2015; Trounson, 2012). The development of the test followed the design of the other international SMTs (Kollmeier et al., 2015; Zokoll et al., 2013) and specified by the International Collegium of Rehabilitative Audiology (Akeroyd et al., 2015).

The UCAMST was adapted from the British English MST (Hall, 2006), with the elimination of vowels that may confuse NZ listeners, and the use of a native NZ English speaker for recording of the sentences (Trounson, 2012). The differences in NZ English formant structure and vowel pronunciation compared to other English dialects (Maclagan & Hay, 2007) necessitated a NZ English version MST.

The UCAST is comprised of a 50-word 5 x 10 base matrix made up of 10 names, 10 numerals, 10 adjectives, 10 verbs and 10 nouns (Figure 4). From this base matrix 5-word sentences are randomly generated that are semantically unpredictable but have a fixed grammatically correct structure. An example of a randomly generated sentence could be 'Peter kept six dark coats'. As can be seen from this example, each word cannot be predicted based on the sentence context and matrix words were recorded separately so that there is co-articulation between them. Each word of the matrix is used only once per list, and each list has ten sentences.

Name	**Verb**	**Quantity**	**Adjective**	**Object**
Amy	bought	two	big	bikes
David	gives	three	cheap	books
Hannah	got	four	dark	coats
Kathy	has	six	good	hats
Oscar	kept	eight	green	mugs
Peter	likes	nine	large	ships
Rachael	sees	ten	new	shirts
Sophie	sold	twelve	old	shoes

Thomas	wants	some	red	spoons
William	wins	those	small	toys

Table 1: The composition of the UCAMST base matrix (Trounson, 2012)

During the test procedure the sentences are presented simultaneously with a fixed level of speech-shaped background noise, while the presentation level of the sentences varies using an adaptive procedure. This determines the speech reception threshold (SRT_{50}) which is the signal to noise ratio where 50% of the words are understood. The UCAST was developed and evaluated for testing speech intelligibility in noise (McClelland, 2015; Stone, 2016) and has also been validated for testing in quiet (Ripberger, 2018).

Due to the high cognitive demand placed on children undergoing testing using the UCAMST a simplified version was developed for testing of paediatric populations (Jenkins-Foreman, 2018).

1.9.2 The simplified version of the UCAMST

The ability to perceive speech in noise is not yet fully developed in children (Buss et al., 2019; Corbin et al., 2016; Leibold & Buss, 2019; Stuart 2005). For this reason, and the fact that children do not yet have a fully developed ability to continually focus on task, (Betts et al., 2006) a simplified version of the UCAMST was developed.

The development of the simplified UCAMST adhered to methodology similar to that used in the development of previously published simplified MSTs. Other simplified MSTs developed for use in paediatric populations include a test in German (Wagener & Kollmeier, 2005), Polish (Ozimek et al., 2012), Finnish (Willberg et al., 2020), Russian (Garbaruk et al., 2020) and Italian (Puglisi et al., 2021). Published data on these simplified paediatric MSTs has shown them to have comparable test-retest reliability to their full adult MST counterparts for testing paediatric populations, despite having fewer words per presentation (Ozimek et al. 2012; Puglisi et al., 2021; Willberg et al., 2020)

The simplified version of the UCAMST has a smaller 18-word 6 x 3 testing matrix (Table 2) and a shorter three-word pseudo-sentence structure, rather than the five-word sentences of the UCAMST. The name and verb columns present in the UCAMST matrix have been removed for the simplified matrix. Additionally, only five out of the ten numerals, adjectives and nouns used in the full version are present in the simplified matrix. Words of lower lexical difficulty were prioritised in the construction of the simplified matrix so that it can be used to test paediatric subjects as young as four years (Jenkins-Foreman, 2018). Additionally, the inclusion of words that generated psychometric functions with steeper slopes were prioritised, to improve the accuracy of the SRT estimates for the simplified UCAMST (Jenkins-Foreman, 2018).

Quantity	**Adjective**	**Object**
two	Big	bikes
three	green	books
eight	new	hats
nine	old	shoes
ten	red	spoons
twelve	small	toys

Table 2: The simplified UCAMST matrix (Jenkins-Foreman, 2018).

There have been limited studies on the use of simplified paediatric versions of matrix sentence tests in adult populations. Willberg and colleagues (2020) have tested the simplified Danish matrix test with an adult population with normal hearing and with an adult population of cochlear implant wearers (Willberg et al., 2021). Results of both studies showed that comparable results can be obtained with the simplified Danish matrix sentence test and the full Danish matrix sentence test even though they differ in length and complexity.

1.9.3 Comparison of the UCAMST and simplified UCASMT

Up to this point the simplified matrix test has been evaluated with normal hearing paediatric listeners to examine its reliability and to obtain reference values (Lay, 2019). The simplified UCAMST has also been tested using a young adult population with normal hearing (Jenkins-Foreman, 2018). However, the simplified UCAMST has not been tested on an adult population with hearing loss, or on a more elderly adult population. The simplified test was originally designed to test paediatric populations but we hypotheses that it may also be suitably for older adults with reduced cognitive ability, such as reduced auditory memory span. This is because of the shorter and less demanding test material and test procedure of the simplified matrix test. A study on the simplified UCAMST by Taylor (2019) on the response order and response time suggests that it is less cognitively demanding than the UCAMST. Additionally, studies have shown that the shorter three-word pseudo-sentences of the simplified matrix tests decrease the effects that attention and fatigue have on the longer 5-word sentences of the original matrix tests (Neumann et al., 2012; Wagner & Kollmeier, 2005).

We hypothesise the 5-word sentences may be too long to assess speech recognition in older adults with reduced working memory, and in these cases the simplified version of the NZ sentence matrix test may be more appropriate.

1.10 Open vs closed set response format:

Both the UCAMST and the simplified UCAMST can be administered in either a closed or open-set response format. For the closed-set response format, the sentence recording is played to the subject who then must select the words in the sentence they heard from a word matrix on a computer screen. For the open-set response format after the sentence is played the subject is required to repeat back to the tester what they heard, and the tester scores the words that were correctly heard and repeated. Both response formats have advantages and disadvantages. The open-set response format requires a tester to be present while the test is being administered, and this tester must speak the language the test is being administered in, as they must score the words correctly repeated. A tester is not required when using the closed-set response format as the scoring is done by the test subject selecting their response from the word matrix on a computer screen. The closed-set response format could even be modified to be administered online.

The literature on the effect of response format on SRT is conflicting. Most studies show lower SRTs using the closed-set response format (Kollmeier, 2015). Representing a better performance when the word matrix was provided as a visual cue (Zokoll et al, 2015). Some studies have shown SRTs to be significantly higher using the closed-set response condition (Hochmuth et al., 2012; Stone, 2016). This effect could be attributable to the greater demand placed on working memory as the listeners have to hold onto the sentence in their short-term auditory memory while also searching and selecting the corresponding word in the matrix (Theunissen et al., 2009). Other studies have found no significant differences between the two response formats (Brand et al., 2004; Ozimek et al., 2010).

Comparison of the SRT for the simplified UCAMST in the open and closed-set response formats have found higher SRTs for the open condition in a population of normal hearing younger adults (Taylor, 2019). This may be due to the advantage the closed-set response format, where all the possible words in the sentence are visible to them as a matrix on the computer screen, gives to the subject.

This research project will assess if the SRTs obtained with the open and closed-set response formats are equivalent for the simplified UCAMST in a population of older hearing-impaired adults.

1.11 Hearing loss, age and speech in noise:

Older adults typically find it more difficult to comprehend speech in noise compared to younger adults (CHABA, 1988; Plomp, 1986; Schneider et al., 2010). Age related hearing loss, especially at high frequencies, is very common, and is known as presbycusis (Davis et al., 2016). With increasing age, the prevalence of hearing loss increases, affecting greater than 40% of people over 50 years old, and approximately 71% of people over 70 years (Wilson et al., 2017).

Hearing loss is known to be associated with increased difficulties with speech perception in noisy listening conditions (Humes & Roberts, 1990; Jerger, et al., 1991; Smoorenburg, 1992). However, it has become clear that it cannot be the only contributing factor as speech in noise hearing ability decreases with age, even when the pure-tone hearing thresholds may not change (Bergman, 1971). Additionally, older adults with similar hearing thresholds can vary in their ability to understand speech in noise, even when the effect of age has been accounted for (Vermiglio et al., 2012). One possible theory is that age-related supra-threshold temporal processing deficits occurring higher up the auditory pathway, which do not affect pure-tone hearing thresholds, but may account for the speech in noise difficulties many older adults experience (Slade et al., 2020; Vermiglio et al., 2012;). This is because auditory perception of speech in noise not only involves peripheral hearing, which is represented by pure-tone thresholds, but also the decoding and comprehension of the speech in noise, which occurs in the higher brainstem and cortical areas (Plack et al., 2014; Presacco et al., 2019).

Multiple studies have shown that aging and declining cognitive ability affect the ability to understand speech in noise, independently of an individual's hearing ability (Ben-David et al., 2012; Buss et al., 2019; Dubno, 2015; Fullgrabe et al., 2015; Goossens et al., 2017; Helfer & Freyman, 2014; Pichora-Fuller et al., 1995).

1.12 Hearing loss and cognitive impairment:

Recent research has identified age-related hearing loss as the largest potentially preventable risk factor for cognitive decline and dementia (Ftouh et al., 2018; Liang et al., 2021; Livingston et al., 2017), with the likelihood increasing with the severity of the hearing loss (Deal et al., 2017; Gurgel et al., 2014; Lin et al., 2011; Lin & Black, 2017). There are three main theories to explain the possible mechanisms between hearing loss and cognitive decline. These are (i) The common cause hypothesis, (ii) the information degradation hypothesis and, (iii) the sensory deprivation hypothesis.

The common cause hypothesis assumes that both age-related hearing loss and cognitive decline are due to a common neurodegenerative pathology. The evidence for this is the parallel changes seen in several perceptual and cognitive domains in aging (Eckert et al., 2019). This led to the theory that the brain atrophy that can be seen in both age-related hearing loss and cognitive ageing may be due to global biological aging affecting global functioning (Slade et al., 2020). However, contrary to this hypothesis is the evidence that there is a causal relationship between hearing loss and cognition, with age-related hearing loss accelerating cognitive decline. The information degradation and sensory deprivation hypotheses are compatible with this evidence.

The information degradation or cognitive load hypothesis postulates that hearing loss in situations where there is a lot of masking noise increases the ‘listening effort’ required for processing and comprehending speech. This increases the demand on limited processing resources. This model of working memory and cognition is based on the idea that the amount of information that can be attended to and held in memory to be used is limited by the processing resources (Wingfield, 2016). In situations of high ‘listening effort’, such as speech in noise, cognitive processing resources are diverted from other cognitive tasks and reallocated to attending to the auditory signal (Tun et al., 2009). This leads to a depletion of cognitive resources and could in theory lead to cognitive decline (Humes et al., 2012). More listening effort is required for older adults compared to younger adults when measured by a dual-task paradigm, with older adult showing poorer performance on the secondary task as they reallocate resources to the primary difficult listening task (Ward et al., 2016). In difficult listening situations more cognitive resources are needed, which leads to resources for other cognitive processes being depleted. Additional support for this hypothesis comes from studies of older adults whose memory performance improved when their auditory perception had been restored by hearing aids, thus reducing the auditory load (Deal et al., 2017; Uchida et al., 2019).

A similar hypothesis to the sensory deprivation hypothesis is the information degradation hypothesis. The difference with the sensory deprivation hypothesis is that it focusses on long-term reallocation of cognitive resources to auditory perception, rather than short term reallocation leading to cognitive decline (Humes et al., 2012). Through long term hearing loss compensatory cortical and neural reorganisation leads to a decrease in general cognitive processes in an attempt to increase auditory perception. Evidence for this theory comes from studies showing increased reliance on frontal brain regions and reduced grey matter in the auditory cortex during speech perception in noise as a compensatory effect in older adults with hearing loss (Du et al., 2016; Eckert et al., 2019; Rosemann & Thiel, 2018). It is hypothesised that sensory deprivation has a direct and indirect effect on cognition. A direct effect through inadequate sensory input, and an indirect effect through decreased communication and socialisation, and an increased incidence of depression (Dawes et al., 2015; Stahl, 2017). It is theorised that reduced social interaction and an increase in social isolation and depression due to hearing loss may mediate the causal relationship between hearing loss and cognitive decline (Dawes et al., 2015; Whitson et al., 2018).

One of the neural changes that is caused by age-related hearing loss is decreased anterior cingulate cortex activation in the cerebral cortex, which may have a direct effect on emotion and mood regulation (Husain et al., 2014). Additionally, anterior cingulate cortex volume in older adults with hearing loss correlates with symptoms of depression (Belkhiria et al., 2019).

In summary, the increased risk for cognitive decline with age-related hearing loss is well established but it is not yet established if there is a causal link between the two factors.

1.12.1 Cognition and speech in noise:

Cognitive abilities play an essential role for speech-in-noise (SIN) understanding (Pichora-Fuller et al., 1995; Pichora-Fuller et al., 2017). The majority of studies on cognition and SIN reception have shown an association between the two variables (Akeroyd, 2008; Dryden et al., 2017). It must be noted however, that this association is most often secondary to hearing loss, with cognition more significantly associated with SIN reception where there is a hearing loss (Akeroyd, 2008; Humes et al., 1994; Humes, 2002; Humes, 2021; Jerger et al, 1991; Rooij & Plomp, 1992). Hearing loss is the primary predictor of speech reception in noise (Akeroyd, 2008). Studies have shown that speech in noise recognition ability may be more sensitive in picking up hearing loss that corelates with lower cognitive ability than pure tone thresholds (Humes et al., 2012). Some have even suggested that SIN tests could be used as a surrogate measure of the cognitive status of a subject (Waters et al., 2021; Zhan et al., 2018).

1.12.2 Cognition Screening:

Mini-Addenbrooke’s Cognitive Examination (Mini-ACE) is a very brief and sensitive screening test for cognitive impairment and dementia that was developed and validated by Hsieh and colleagues, in 2015. The test is an abbreviated version of the Addenbrooke’s Cognitive Examination III (ACE-III) developed using statistical data reduction methods.

In September 2020 the Mini-ACE replaced the Montreal Cognitive Assessment (MoCA®) as the recommended screening test for cognitive impairment for use in the NZ health sector (Cognitive Impairment Assessment Review Working Group, 2020). Unlike the MOCA®, the Mini-ACE is widely available, can be used free of charge and only takes about five minutes to complete.

There are three versions of the Mini-ACE test (A, B and C), which only differ in the memory section of the test, to avoid learning effects when the test is being used for longitudinal monitoring. As well as memory, the Mini-ACE also assesses attention, recall, orientation, verbal fluency, language and visuospatial function (Larner, 2020).

The test has a maximum score of 30 and higher scores are associated with better cognitive function (Beishon et al., 2019). There are two cut-off scores for screening research participants and clinical patients. The first is a score of 25/30 which has good sensitivity

(61%) and specificity (87%) for dementia, with scores of 25 or below being 5 times more likely to have come from a patient with dementia than without (Larner, 2015a, Larner 2015b). The second cut off score of 21/30 or below has a higher specificity (100%) for dementia and is the recommended cut-off when Mini-ACE is used to screen general populations (Larner, 2019). Independent studies of Mini-ACE have verified its ability to detect cognitive impairment in different clinical settings (Beishon et al., 2019; Hobson et al., 2016; Larner, 2020; Miranda et al., 2018).

However, it must be remembered that as it is a screening test the Mini-ACE should not be used in isolation to make a diagnosis of dementia. For such a diagnosis further neuropsychological and cognitive tested are needed.

1.13 The present study rationale and aims

1.13.1 Reliability and Accuracy of estimating speech-in-noise SRT in older adults with a hearing loss and potential cognitive decline

Owing to the cognitive demands of the UCAMST which is based on a conventional Hagerman MST (Hagerman, 1982) comprising a large 5 by 10-word matrix, the current research project aimed to assess if the simplified UCAMST with a smaller 6 by 3-word matrix would be more suitable for testing of older adults with a hearing loss and who may also have cognitive impairment. The simplified UCAMST is hypothesised to be better suited for use in older adults with a hearing impairment and cognitive impairment due to its shorter 3-word pseudo sentence structure and smaller word matrix, which should minimise the impacts of cognitive load, working memory and fatigue. If the effects of increased cognitive load are minimised, we hypothesise that the reliability and sensitivity of an individual's SRT will be increased.

Despite having fewer words per trial, we hope the simplified UCASMT test-retest reliability will be comparable to data previously obtained with the UCAMST.

If the simplified UCAMST can be shown to estimate speech-on-noise SRTs in a typical population presenting to an Audiology clinic in NZ, this progresses the test towards clinical uptake.

1.13.2 Cross validation of simplified UCAMST with the QuickSIN™ test:

Currently, if speech in noise is tested in the NZ clinical setting the QuickSIN™ test is most commonly used. However, the QuickSIN™ is in American English which can lead to inaccurate results when used with native NZ English speakers. For this reason, and the other previously discussed advantages speech testing with a MST has over the QuickSIN™ , it is proposed that the UCAMST will be the speech in noise test of choice in NZ clinics.

Toward this end one of the aims of the current study was to cross validate the simplified UCAMST with the QuickSIN™ test in a typical population presenting to a NZ audiology clinic. Previous research (albeit with a low number of participants) has established a correlation between the results obtained with the UCAMST and the QuickSIN™ (Andre, 2016). This study aimed to establish if the correlation was seen with the simplified UCAMST and the QuickSIN™.

1.14 The present study research questions and null hypotheses:

Are the simplified UCAMST open- and closed-set response formats equivalent with regards to SRT_{50} *and slope?*

Null Hypotheses:

1. The test-retest reliability of the simplified UCAMST within individuals is not significantly different in the open-set response mode vs the closed-set response mode.
2. There is no significant difference between the SRT_{50}s from the simplified UCAMST in the open-set format compared to the closed-set format
3. There is no significant difference between the slopes from the simplified UCAMST in the open-set format compared to the closed-set format.

Is the simplified UCAMST affected by increasing age?

Null Hypotheses:

1. The test-retest reliability of the simplified UCAMST within individuals is not significantly affected by the participant's age.
2. There is no significant correlation between a participants SRT_{50} from the simplified UCAMST and their age.

Is the simplified UCAMST affected by different levels of hearing loss?

Null Hypotheses:

1. The test-retest reliability of the simplified UCAMST within individuals is not significantly affected by the participants severity of hearing loss.
2. There is no significant correlation between a participants SRT_{50} from the simplified UCAMST and their hearing ability.

Is the simplified UCAMST affected by the cognitive status of the individual being tested as represented by their score on the Mini-ACE?

Null Hypotheses:

1. The test-retest reliability of the simplified UCAMST within individuals is not significantly affected by the participants cognitive score on the Mini-ACE.
2. There is no significant correlation between the participants SRT_{50} from the simplified UCAMST and their score on the Mini-ACE

Is there any significant correlation between results from the simplified UCAMST and those from the QuickSIN™ test?

Null Hypotheses:

1. There is no significant correlation between SRT_{50}s from the simplified UCAMST and the SNR_{50} of the QuickSIN™ test

Chapter 2

Methods

2.1 Overview

The University of Canterbury Human Ethics Committee reviewed the current research project and approved it before any testing commenced. All research methods complied to the approved ethics proposal. A copy of the letter of approval from the University Human Ethics Committee can be found in Appendix A.

All testing of participants for this study took place on site in a dedicated research room at the University of Canterbury School of Psychology, Speech and Hearing. All tests were conducted within a sound-treated audiological testing booth within this room, apart from the Mini-Ace cognitive test, which was conducted outside the testing booth, in the research room itself.

2.2 Participants

2.2.1 Recruitment

Participants were primarily recruited from the University of Canterbury School of Psychology, Speech and Hearing client database. The School runs a paid hearing clinic open to the public. The clients in the hearing clinics database have given their permission to be contacted for voluntary participation in research studies. An email invitation, along with an information sheet on the current study (Appendix B), was sent to 109 people that fulfilled the inclusion criteria.

2.2.2 Inclusion criteria

The inclusion criteria for the study were that participants be native speakers of New Zealand English. This was to ensure that the validity of the application of the UCAMST in a New Zealand clinical setting was not compromised. Previous research has shown that a listener's speech intelligibility scores can be significant reduced when listening to a non-native speaker (van Wijingaarden et al., 2002; Zokoll et al., 2013). Additionally, participants were required to be adults of greater than 18 years old. The testing protocol was 90 to 120 minutes long and required a high level of attention and concentration. As an individual's capacity to pay constant attention and concentration to a task continues to develop through adolescence (Betts et al., 2006) the current study focused only on adults. Due to some of the testing being done with a closed-set format response mode the participants were required to have visual acuity that allowed them to read text on a computer screen, this could be with the aid of their normal corrective lenses. Additionally, to be able to select words via a touch screen in the closed-set response mode, the participants could not have any chronic dexterity problems that inhibited them from doing this.

A $20 Motor Trade Association voucher was presented to all study participants as a token of appreciation for giving up their time to participate in this study.

2.3 Experimental Procedures:

On arrival at their testing appointment each participant was given a consent form to read and sign. A brief explanation was given to them about what was required, that supplemented the information sheet that had already been emailed to them. All participants were given the opportunity to ask any questions before testing started, and throughout the duration of testing. Instructions for each test were given immediately prior to the start of each different test so the participant understood exactly what was expected of them. All pure tone audiometry and speech testing of participants was done unaided (i.e., The participants were required to remove their hearing aids if they wore them).

2.3.1 Cognitive screening with the Mini-ACE test

All participants underwent screening for mild cognitive impairment or dementia with the Mini-ACE screening tool. The author undertook the New Zealand online training module through the Ministry of Health to acquire certification to administer the Mini-ACE test. A copy of certification of the completion of this training can be found in Appendix C.

The first part of the Mini-Ace test involves gathering the following information on the participant being screened; their date of birth, their age at leaving full time education, their occupation, and whether they are right or left-handed. This is all recorded at the top of the test sheet. The screening test itself is composed of five sections, each composed of a single task. The first section is a test of attention, with the subject being asked what the date is, including the day of the week, month, and year.

The second section is a memory task where the subject must repeat back a name and address given to them by the tester. This is repeated three times, so the subject has an opportunity to learn and commit to memory the name and address. They are told to try to retain it in their short-term memory, as they will be asked to repeat it back in a few minutes, at the end of the test.

The third section is a fluency task where the participant is asked to name as many animals as they can in 60 seconds.

In the fourth section the subject is asked to draw a clock face, including all the numbers, with the two hands showing ten past five. In the final section, the participant is required to repeat back as much of the name and address that they remember learning in section two. Each part of the name and address remembered is worth one point, with a possible total of seven. Each participant's score is added up and represented as a total out of thirty. There are two clinically relevant cut-offs. The first being a score of 25 or under out of thirty, and the second being 21 out of thirty or under. The Mini-ACE has three versions (A, B and C), with the only difference being the name and address used in the memory section. The version given to a participant was randomised.

2.3.2 Pure Tone Audiometry

The Hearing threshold of all participants was assessed with pure tone audiometry using the modified Hughson Westlake procedure (Carhart & Jerger, 1959) at octave frequencies between 250 and 8000 Hz in accordance with the New Zealand Audiological Society best practice guidelines (NZAS; 2016). If there was a 20 dB or greater difference between two adjacent octave frequencies, then the inter-octave frequency was tested as well.

Pure tone audiometry for both air and bone conduction thresholds was carried out using either a calibrated AC40 or GSI 61 clinical audiometer. Pure tone stimuli were presented via Telephonics TDH-50P supra-aural headphones or with foam inserts to obtain air conduction thresholds. Bone conduction thresholds at 500, 1000, 2000 and 4000 Hz were obtained using a RadioEar B-71 bone transducer. Participants responded to the pure tones they heard by pressing a response button connected to the clinical audiometer.

2.3.3 Categorization of hearing impairment groups

Based on the pure tone audiogram each participant's ear was categorized into one of seven different hearing ability groups according to their pure tone average (PTA). Pure tone averages were calculated as the mean of the four hearing thresholds at 500, 1000, 2000, and 4000 Hz. A four frequency PTA was calculated with the inclusion of the 4000 Hz threshold because of its importance for speech perception (Smoorenburg, 1992; Vermiglio et al., 2012; Vermiglio et al., 2019).

The seven hearing ability groups were as follows, normal hearing, slight hearing impairment, mild hearing impairment, moderate hearing impairment, moderately severe hearing impairment, severe hearing impairment and profound hearing impairment. These hearing ability groups were based on Goodman's severity classification scale for hearing loss (Goodman, 1965). The Goodman classification scheme is the most used hearing classification scheme internationally (it is the American Speech–Language–Hearing Association standard) and in New Zealand.

Degree of Hearing loss (in dB HL)	**Goodman classification**
-10 to 15	Normal hearing
16 to 25	Slight
26 to 40	Mild
41 to 55	Moderate
56 to 70	Moderately severe
71 to 90	Severe
> 91	Profound

Table 3: Goodman Classification scheme for severity of hearing loss

2.4 Speech in noise testing

2.4.1 Quick Speech in Noise (QuickSIN^{TM}) test procedure

A Compact Disc (CD) of the QuickSIN^{TM} version 1.3 test from Etymotic Research Inc was played through a Sony Walkman CD player connected to an AC40 audiometer. This enabled the QuickSIN^{TM} to be routed through the speech circuit of the audiometer and played through either circumaural or insert transducers.

Before testing of each participant, the QuickSIN^{TM} CD was calibrated using the 1 kHz calibration tone (track 1) on the CD so both channels of the audiometer read 0 on the UV meter. The test sentence stimuli were presented at 70 dB HL unless the participant had a pure tone average of greater than 50 dB HL, in which case the test was presented at a level that was "loud but ok". The tests four-talker babble (three females, one male) noise is played simultaneously at SNRs of 25 to 0 dB decreasing in 5 dB steps for the sentences in each list. Instructions for the test were read off a set script provided in the test manual (Figure 4) immediately before testing started, and verbal confirmation was sought from each participant that they understood the instructions.

> *"Imagine that you are at a party. There will be a woman talking and several other talkers in the background. The woman's voice is easy to hear at first, because her voice is louder than the others. Repeat each sentence the woman says. The background talkers will gradually become louder, making it difficult to understand the woman's voice, but please guess and repeat as much of each sentence as possible."*

Figure 4: Test instructions for the QuickSIN^{TM} speech in noise test given to each participant. From the QuickSIN^{TM} version 1.3 user manual (Etymotic Research Inc).

Each participant was played two practice lists (CD tracks 21 and 22) to determine the correct presentation level and to familiarise the subject to the test protocol. These practice lists were not included in the final data analysis.

All participants were tested with six lists of six QuickSIN™ sentences. Two lists of sentences were presented to the right ear, two lists to the left ear, and two lists were presented binaurally. The masking babble noise was played simultaneously into the same ear for the monoaural testing conditions and into both for the binaural testing condition.

2.4.2 Scoring of the QuickSIN™ test:

To score the QuickSIN™ test the number of correctly identified keywords in each sentence for all six sentences in one list were added up. This was added to the total of the list presented in the same condition. For example, the total of correctly identified keywords for both lists presented to the right ear were added together to get an average of two lists.

2.4.3 Calculating the SNR_{50} and SNR loss for the QuickSIN™ test

For the QuickSIN™ test the SNR represents a cumulative distribution function (CDF) and the mean of this function is taken as the estimate of the SNR_{50}. The Spearman-Karber method (Finney, 1952) was used to calculate the mean using the following equation:

$$SNR_{50} = i + \frac{d}{2} - \frac{(d\#correct)}{w}$$

where *i* is the initial SNR presentation level (dB), *d* is the step size between SNR conditions (dB), *#correct* the total number of correctly recognized keywords in the set of sentences and *w* is the number of test items per SNR (= the number of keywords in each sentence). As the QuickSIN™ has 5 keywords in each sentence and a step size of 5 dB, SNR_{50} is calculated as

$$SNR_{50} = 25 + \frac{5}{2} - \frac{5\ (\#\ correct)}{5}$$

The SNR loss is defined as the dB increase in the SNR_{50} compared to the population mean which is calculated as SNR_{50} - 2 dB. Therefore, SNR loss = 25.5 – (# correct)

The SNR loss was compared to a normative table (Table 4) which classified the participants SNR loss as normal/near normal, mild, moderate or severe.

SNR Loss (dB)	Degree of SNR Loss
0-3	Normal/near normal
3-7	Mild SNR loss
7-15	Moderate SNR loss
>15	Severe SNR loss

Table 4: *How to interpret QuickSIN™ SNR loss score (Adapted from QuickSIN™ version 1.3 speech in noise test user manual, Etymotic Research Inc.)*

2.5 Matrix Sentence Testing in Noise procedure

2.5.1 Instrumentation

Participants were seated in a soundproof booth alongside the tester in front of a computer installed with the UC Adaptive Speech Test (UCAST) Platform. The software was developed in LabVIEW™ (National Instruments, 2018) by Professor Greg O'Beirne and ran on an HP Elitebook 830 G5 laptop. The graphical user interface of the UCAST platform can be seen in Figure 5. All the testing conditions were selected from this interface.

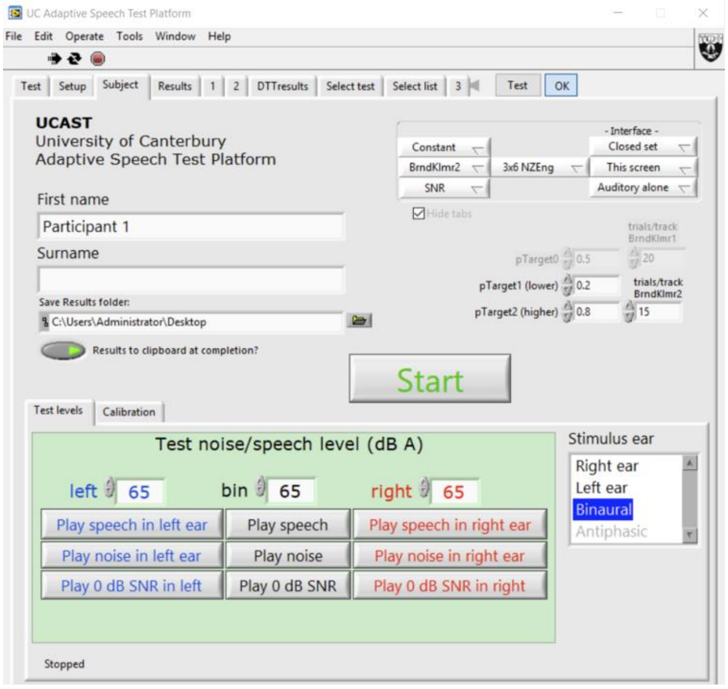


Figure 5: Graphical user interface of the University of Canterbury Adaptive Speech Test platform.

The sentences and masking noise were played simultaneously through Sennheiser (Sennheiser electronic GmbH & Co.KG, Germany) HD 280 Pro (64 Ω impedance) circumaural headphones which were connected to the HP Elitebook 830 G5 via a Sound Blaster SBX Pro studio external sound card (Creative Labs, Singapore).

2.5.2 Test conditions and order

All participants were tested with the simplified UCAMST in both the open and closed response test condition. Additionally, data collection for this research project was co-ordinated with another student who was investigating the performance of the simplified UCAMST in testing speech in quiet within the same population. This meant that all participants were tested for all conditions both in quiet and with background noise.

All testing conditions were put into a testing matrix and randomised, to avoid any order bias. This matrix dictated what in what order each test was administered to each participant (Appendix 3).

Due to the length of the testing procedure and the level of concentration required, participants were asked if they required a break at the halfway point when 6 of the 12 conditions had been completed.

Participants also underwent testing with CVC words in quiet after audiometry as part of the other student's project. The data for all quiet test conditions will not be analysed or discussed in this thesis, but will be published in another thesis (McGill, in preparation).

Verbal instructions were given to the participant explaining that they would hear a three-word sentence in the presence of background noise that would vary in intensity (or alternatively be in quiet with no background noise). Participants were instructed to repeat verbally what they heard for the open-set response condition or select their answer from the word matrix on the touchscreen for the closed-set response condition.

2.5.3 Closed-set response condition

In the closed-set condition the participant was required to input what they heard through a touch sensitive computer monitor. They were encouraged to guess if they were unsure of what they heard. The test required an answer to be entered after each 3-word sentence presentation. If they heard nothing, participants still had to select one word from each column of the word matrix for the test to continue.

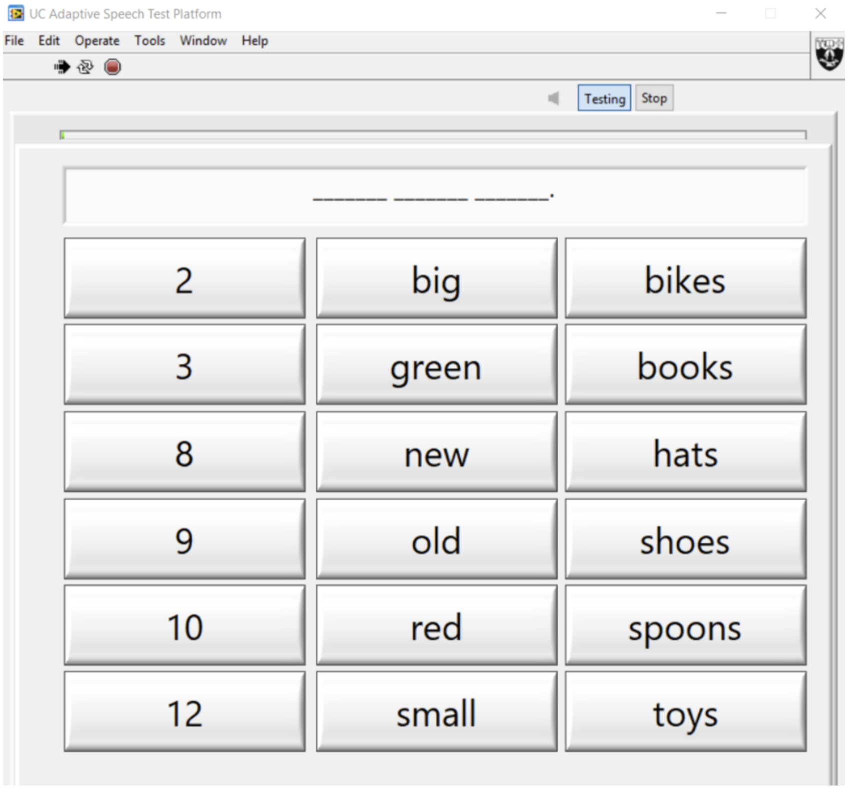


Figure 6: The simplified UCAMST response panel used by the participant in the closed-set response condition

2.5.4 Open-set response condition

In the open-set condition the participant were asked to repeat back verbally to the tester verbatim what they heard. The tester scored the responses using a graphical user interface (GUI) on a touch screen computer screen which showed the three words of the sentence that had been presented (Figure 7). If the participant did not respond at all after a sentence had been presented the next button was pushed by the tester. The computer screen was not visible to the participants and no feedback was provided to them after the presentation of the sentence.

Figure 7: The layout of the scoring screen that was used by the tester to record the participants responses for the simplified UCAMST in the open-set mode.

2.5.5 Sentence stimuli

Thirty sentences of three words each were presented for each test condition which were randomly selected by the software. The sentences were presented monaurally at 65 dB SPL.

2.5.6 Noise stimuli

The masking noise used was a constant speech-shaped noise produced specifically for the UCAMST (Trounson, 2012). Audio recordings were randomly overlaid 10,000 times to produce a constant noise with spectral content nearly identical to that of the signal. The noise level for all conditions was set at 65 dB SPL and was played monoaurally simultaneously into the same ear as the sentence stimuli. The noise was turned on and off 500 ms before and after the presentation of each sentence. The signal-to-noise ratio (SNR) was determined by the speech signal level which was varied for each presentation using an adaptive tracking procedure as detailed below.

2.5.7 Practice lists

To reduce training effects all participants completed two practice lists that were not included in the final data analysis, as recommended by Kollmeier (2015). The practice lists were presented binaurally in closed set format so that the participant could gain knowledge of the structure of the sentence matrix and the words that it contained, as well as the adaptive procedure. The practice lists also ensured that the participant understood the task and allowed their performance to stabilise before real data was collected (Deitz et al., 2014; Kollmeier et al., 2015; Wagener et al., 2003).

2.5.8 Scoring

The number of words correctly identified in an individual sentence were scored. Each sentence had a maximum score of three if all three words were correctly identified.

2.5.9 Adaptive tracking procedure

The dual track procedure proposed by Brand and Kollmeier (2002), the so-called pair of compromise method, was used to adaptively track two points corresponding to 20% and 80% correct responses. The simplified UCAMST software was programmed to execute this dual adaptive track procedure using 15 sentences to estimate the 20% correct response point, and 15 sentences to estimate the 80% correct response point. Therefore, a total of 30 sentences are presented for each test condition.

The constant noise remained fixed at 65 dB SPL and the presentation level of the sentence stimuli were varied in steps according to the participants previous response. The step size adaptively changed based on how many of the words in the previous sentence were correctly recognized.

Tracking two points simultaneously allows the slope and the psychometric function to be concurrently estimated. The SRT_{50}, which is the SNR that is needed to correctly recognize 50% of the test material, was estimated by fitting the test data using the maximum-likelihood procedure to the test-specific psychometric function (Kollmeier et al., 2015).

2.6 Statistical analysis

Statistical analysis was carried out using the open source statistical software packages Jamovi v 2.2.5 (The Jamovi project, 2021) and JASP v 0.16 (JASP team, 2022).

Chapter 3

Results

As is common in the published literature, for this data analysis the left and right ear measurements from an individual participant were treated as being independent. Follow-up analysis was also carried out on combined left and right ear data. Parametric statistical test methods were used as normalcy of the data was assumed because of the large size of the data set. The Shapiro-Wilk test was also used to conform the normality of the data set.

3.1 Descriptive statistics

3.1.1 Participants

Participants (n = 64), ranging in age from 30 to 87 years (Mean = 69.3 years), were recruited and tested for the current research project, with approximately equal numbers of male and females (n = 33 males, and n = 31 females). One female participant was removed from the dataset at the end of data collection due to the difficulty she had hearing and following the test instructions which was reflected in her outlying results.

3.1.2 Pure tone thresholds

The average of the 500, 1000, 2000 and 4000 Hz frequencies (4F PTA) was calculated for each ear of all participants. This 4F PTA was then used to classify each ears hearing ability, using the Goodman classification scale (Table 5). Based on this classification 5 participants were found to have normal hearing binaurally and 2 participants were found to have 1 ear each that are classified as normal hearing. So, a total of 12 ears had a classification of normal hearing based on the 4F PTA being less than 16 dB HL. These 12 ears were removed from the main data set.

Degree of Hearing loss (in dB HL)	Goodman classification	Number of participants REs	Number of participants LEs
-10 to 15	Normal hearing	6*	6*
16 to 25	Slight	9	8
26 to 40	Mild	20	23
41 to 55	Moderate	20	20
56 to 70	Moderately severe	8	5
71 to 90	Severe	0	1
> 91	Profound	0	0

**These normal hearing ears were removed from the main data set*

Table 5: Hearing classifications of participants based on their pure tone audiometry results

The average of the pure tone thresholds across frequencies, of all ears that didn't have normal hearing, was calculated using three different methods, each method including different frequencies in the calculation. The results of these calculations can be found in Table 6.

	3F PTA (SD)	4F PTA (SD)	HF PTA (SD)
Participants Right Ears (n=57)	33.1 (±14) dB HL	38.6 (±13.1) dB HL	61 (±15.7) dB HL
Participants Left Ears (n=57)	34.5 (±13.9) dB HL	40 (±13.1) dB HL	61.7 (±17.5) dB HL
All ears combined (n=114)	33.8 (±13.9) dB HL	39.3 (±13.1) dB HL	61.3 (±16.5) dB HL

3F PTA = average of 500, 1000 and 2000 Hz frequencies; 4F PTA =average of 500, 1000, 2000 and 4000 Hz frequencies; HF PTA = average of 4000, 6000 and 8000 Hz frequencies

Table 6: Pure tone threshold averages across different frequencies for all participants

The mean 3F PTA and the 4F PTA for both left and right ears, and all ears combined represents a mild hearing loss according to the Goodman's severity classification scale for hearing loss (Refer Table 5). The HF PTA for both left and right ears, and all ears combined represents a moderately-severe high frequency hearing loss according to the Goodman's classification scale. The HF PTA takes an average of just the high frequencies of 4000, 6000 and 8000 Hz and these results reflect the fact that the majority of participants had a sloping high frequency hearing loss configuration on the audiogram.

A graph of all average pure tone thresholds across all frequencies for all participants is shown in Figure 8.

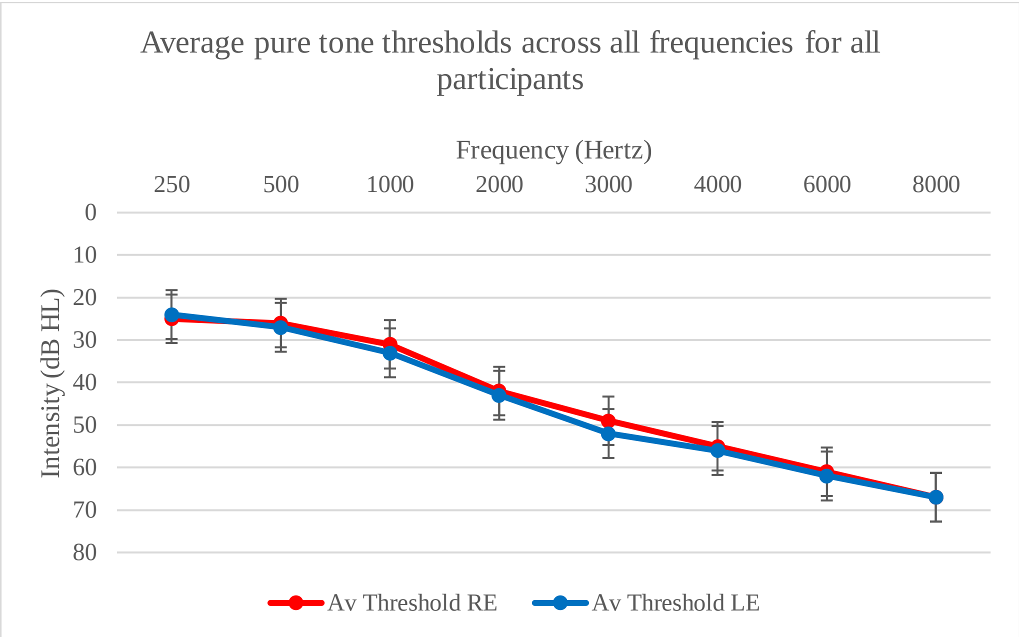


Figure 8: Average pure tone thresholds of participants. Error bars represent the standard deviation of the threshold at each frequency.

3.1.3 Mini-ACE

The mean score on the Mini-ACE test for all participants was 26.6 (± 3.10). The range of scores on the Mini-ACE test was 14 to 30. Fourteen participants failed the Mini-ACE cognitive screen as they scored under the 25 or below cut off point. Four of these participants scored below the 20 or below cut off point. The cut-off point of ≤ 25/30 has a high sensitivity and the cut-off point of ≤ 20/30 has high-specificity and a score above either cut-off excludes dementia and mild cognitive impairment (Larner, 2019). So, the fourteen participants that scored 25 or below were considered to have a high likelihood of some cognitive impairment (Beishon et al., 2019).

The relationship between the participants age and their score on the Mini-Ace can be visualised in the scatterplot in figure 9.

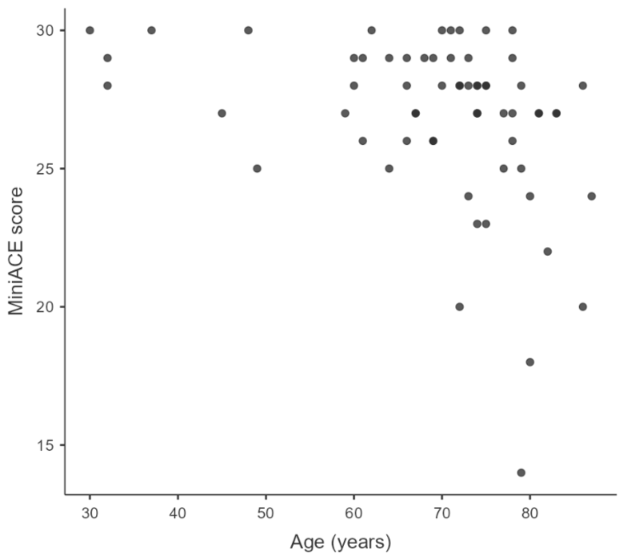


Figure 9: Relationship between a participants age and their score on the Mini-ACE cognitive screen.

3.1.4 QuickSIN™

The mean SNR_{50} value obtained from the QuickSIN™ test for all participants right ears was 17.6 dB SNR (SD ± 6.3). The range of SNR_{50} values was 3 to 26.5 dB SNR. The mean QuickSIN™ SNR loss score for all participants right ears was 15.6 dB SNR (SD ± 6.3) which is classified as a severe SNR loss. The range of SNR loss scores was 1 dB SNR (normal SNR) to 24.5 dB SNR (severe SNR loss).

The mean SNR_{50} value obtained from the QuickSIN™ test for all participants left ears was 16.4 dB SNR (SD ± 6.1). The range of SNR_{50} values was 4 to 26 dB SNR. The mean QuickSIN™ SNR loss score for all participants left ears was 14.4 dB SNR (SD ± 6.1) which is classified as a moderate SNR loss. The range of SNR loss scores was 0.5 dB SNR (normal SNR) to 24 dB SNR (severe SNR loss).

The mean SNR_{50} value obtained from the QuickSIN™ test for all participants in the binaural condition was 20.8 dB SNR (SD ± 4.7). The range of SNR_{50} values was 9 to 26.5 dB SNR. The mean QuickSIN™ SNR loss when the QuickSIN™ was administered in the binaural condition was 18.6 dB SNR (SD ± 4.7) which is classified as a severe SNR loss. The range of binaural SNR loss scores was 7 dB SNR (mild SNR loss) to 24.5 dB SNR (severe SNR loss).

3.1.5 Simplified UCAMST in the open response format

The SRT_{50} in the open response format (n=82) had a mean of -5.91 dB SNR (SD ± 2.26). The SRT_{50} values ranged from -9.70 to 0.90 dB SNR. A box-plot of the SRT_{50} open response data shows that there were no outlying data points (Figure 10).

3.1.6 Simplified UCAMST in the closed response format

The SRT_{50} in the closed response format (n=82) had a mean of -8.67 dB SNR (SD ± 2.31). The SRT_{50} values ranged from -13.9 to -3.6 dB SNR. A box-plot of the SRT_{50} data in the closed format shows that there were no outliers in the dataset (Figure 10).

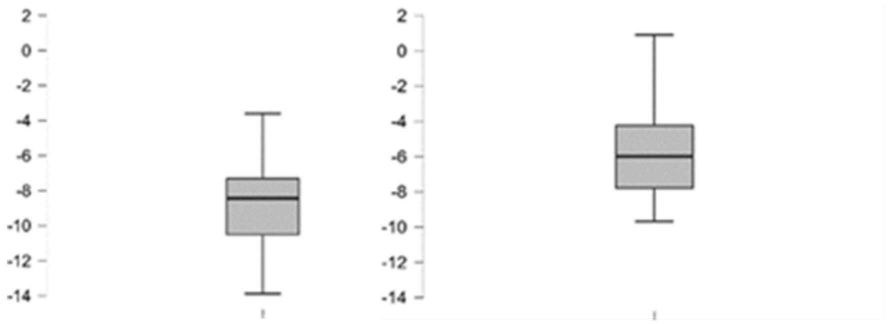


Figure 10: Box-plot of SRT_{50} closed-set (left) and open-set (right) response data.

3.1.7 Intelligibility functions for individual participants

Once the SRT_{50} values and the slopes for individual participants were calculated, individual intelligibility functions could then be plotted (Figure 11). The mean slope for the closed-set condition was 10 ± 8%/dB. The mean slope for the open-set condition was 27 ± 116%/dB. The steeper slope of the open-set condition indicates that the accuracy of SRT_{50} estimates will be higher, but the high standard deviation seen in the slope values indicates that the data is more widely spread, so less reliable.

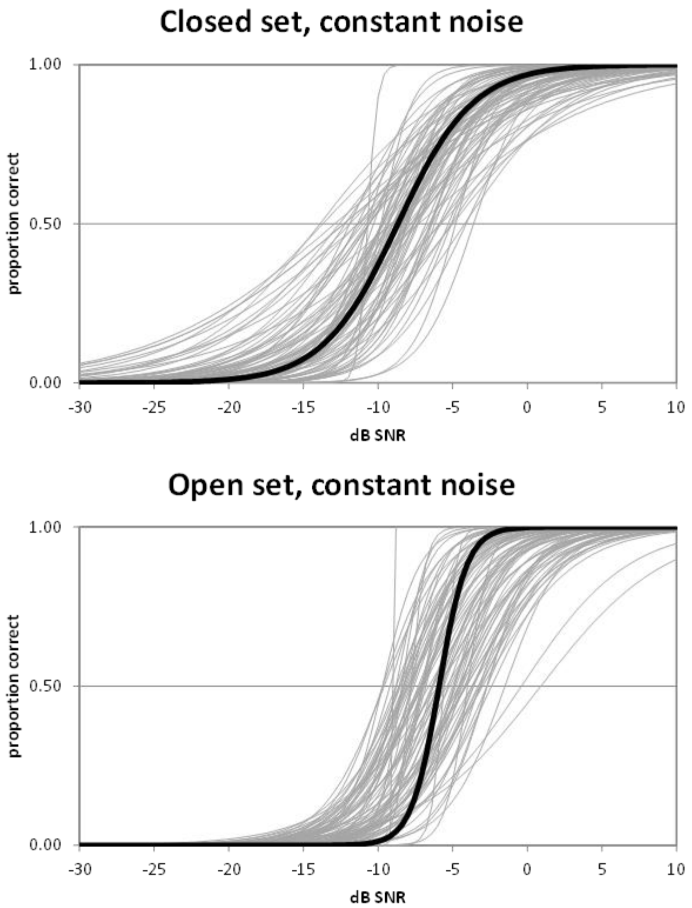


Figure 11: The speech intelligibility functions of the simplified UCAMST in the closed-set (Top panel) and open-set (Bottom panel) conditions. The individual results for all participants are plotted in grey, and the average of the intelligibility functions is plotted in black.

When the trial and retrial data were averaged together the following results were obtained. The mean SRT_{50} in the closed format response mode averaged over two trials for all test subjects was -8.32 dB SNR (SD ± 2.47), and the mean slope was 10 ± 9%/dB. The mean SRT_{50} in the open format response mode averaged over two trials for all test subjects was -5.67 dB SNR (SD ± 2.38), and the mean slope was 13 ± 8%/dB.

3.2 Test-retest reliability analysis

The test-retest reliably of the simplified UCAMST and the QuickSIN™ tests were ascertained by carrying out two different statistical methods. Firstly, a Cronbach analysis (Cronbach, 1951) was done to determine an alpha level of reliability. Cronbach's alpha is a measure of internal consistency and higher levels of alpha reflect a higher ability of the test to give the same result when the test is repeated. Secondly, a statistical measure proposed by Plomp and Mimpen (1979) was used where test-retest reliability is calculated as the root mean square of the within-subject standard deviations of repeated measures of SRTs. This second measurement has been used extensively to evaluate MSTs in the literature (Brand & Kollmeier, 2002; Jansen et al., 2012; Warzybok et al., 2020). For the purpose of this study we will call this second method simply the measurement error.

3.2.1 Test-retest reliability of the QuickSIN™ test

The test-retest reliability of the QuickSIN™ was calculated within the current study population so that the reliability of the QuickSIN™ and the simplified UCAMST could be directly compared.

The Cronbach alpha levels as well as the test-retest reliability measure obtained for two repeated measures of the QuickSIN™ test for n=57 participants in the monoaural condition for each ear and the binaural condition are shown in Table 7.

QuickSIN™ test condition	Cronbach's alpha	Measurement error (dB)
Right ear	0.94	±1.29
Left ear	0.91	±1.46
Binaural	0.86	±1.47

Table 7: Cronbach's alpha level for the monoaural and binaural condition of the QuickSIN™ test based on two repeated measures.

3.2.2 Test-retest reliability of the simplified UCAMST

The Cronbach alpha levels and the test-retest measure obtained from two repeated measures of the simplified UCAMST for each participant are shown in Table 8. Cronbach alpha levels and the test-retest measure were calculated for both the open and closed-set response conditions for both left and right ears separately and for both ears combined. The means of the SRT_{50} for the first test and the retest for the closed condition (t (54) = 0.915, p = 0.364, mean difference = 0.313 dB, SE difference = 0.342 dB, Cohen's d effect size = 0.123 (CI -0.142 - 0.388)) and the open condition (t (56) = 0.652, p=0.517, mean difference = 0.617 dB, SE difference = 0.256 dB, Cohen's d effect size = 0.0864 (CI - 0.174 - 0.346)) were not significantly different.

Condition	**Cronbach's alpha**	**Measurement error (dB)**	**Mean SRT_{50} of test 1 (SD) (dB SNR)**	**Mean SRT_{50} of retest (SD) (dB SNR)**
RE closed (n=28)	0.69	±0.84	-8.8 (±2.5)	-8.4 (±1.8)
LE closed (n=27)	0.67	±1.09	-7.5 (±2.2)	-8.6 (±3.1)
All ears closed (n=55)	0.65	±0.96	-8.2 (±2.4)	-8.5 (±2.5)
RE open (n=28)	0.74	±0.81	-5.9 (±2.4)	-5.8 (±2.2)

LE open (n=29)	0.86	±0.69	-5.3 (±2.7)	-5.7 (±2.2)
All ears open (n=57)	0.81	±0.75	-5.6 (±2.6)	-5.8 (±2.2)

Table 8: Cronbach's alpha level for the simplified UCAMST in both the open and closed response mode based on two repeated measures.

The higher Cronbach's alpha for the open response format (0.81) compared to the closed response format (0.65) indicates that the open response format of the simplified UCAMST is more reliable.

The measurement error for the open condition was ± 0.75 dB compared to ± 0.96 dB for the closed condition. This indicates there is less variability and hence a smaller measurement error in the open condition compared to the closed condition.

The difference in the mean SRT_{50}s between the test and retest in the open condition show a comparative improvement in the retest SRT_{50} of 0.2 dB. The difference in the mean SRT_{50}s between the test and retest in the closed condition shows a comparative improvement in the retest SRT_{50} of 0.3 dB.

Overall, when comparing the open and closed-set conditions the participants performed better in the closed-set condition, as reflected in the lower SRT_{50}s in the closed condition. The mean SRT_{50} was -8.4 dB SNR for both closed-set test and retest conditions combined, compared to a SRT_{50} of -5.7 dB SNR for the test and re-test open conditions combined.

3.2.3 Effect of cognitive status on the reliability of the simplified UCAMST

The Cronbach alpha level was also calculated after the 14 participants that had failed the Mini-ACE cognitive screen were removed from the dataset. The effect this had on the Cronbach alpha levels can be seen in Table 9. Removing those participants who failed the Mini-ACE increased the alpha levels for the “all ears” data set in both the closed and open-set conditions. This indicates that the simplified UCAMST became more reliable when participants who may have mild cognitive impairment, were removed.

Condition	**Cronbach’s alpha**	**Measurement error (dB)**	**Mean SRT_{50} of test 1 (SD) (dB SNR)**	**Mean SRT_{50} of retest (SD) (dB SNR)**
Closed condition				
All participants (n=55)	0.65	±0.96	-8.2 (±2.4)	-8.5 (±2.5)
Only participants that passed Mini-ACE (n=43)	0.67	±0.96	-8.5 (±2.7)	-8.5 (±2.3)
Open condition				
All participants (n=57)	0.81	±0.75	-5.6 (±2.6)	-5.8 (±2.2)
Only participants that passed Mini-ACE (n=44)	0.84	±0.35	-5.8 (±2.7)	-6.0 (±2.3)

Table 9: Effect of removing the participants that failed the Mini-ACE cognitive screen on the test-retest reliability and variance of the simplified UCAMST in both the open and closed response mode based on two repeated measures.

The measurement error for the closed format condition remained the same when the participants that had failed the cognitive screen were removed from the data set.

The measurement error for the open format condition decreased by 0.40 dB when the participants that had failed the cognitive screen were removed.

The mean SRT_{50} of the first test and the retest averaged for the closed condition was -8.49 dB SNR. When the SRT_{50} scores of the participants that failed the mini-ACE screen were removed the mean SRT_{50} shifted by 0.17 dB to -8.32 dB SNR. For the open condition the mean SRT_{50} of the first test and the retest averaged was -5.67 dB SNR. When the participants who failed the cognitive screen were taken out of this dataset the mean SRT_{50} improved by 0.19 dB to -5.86 dB SNR.

3.2.4 Effect of age on the reliability of the simplified UCAMST

To assess the effect of the subjects age on the reliability of the simplified UCAMST in both the open and closed response format, the data was split into two groups, the first was younger participants aged < 74 years (n = 30), and the second group was older participants, aged ≥ 74 years (n = 25). The mean age of the younger group in the closed response condition was 64.9 years (SD ± 9.19) with the ages ranging from 32 to 73 years. The mean age of the older group in the closed response condition was 78.1 years (SD ± 3.89) with the ages ranging from 74 to 87 years.

For the open response condition, the data was likewise split into the same two age groups, those younger than 74 years (n = 29) and those 74 years and older (n = 28). The mean of the younger group was 66 years (SD ± 6.89), with the ages ranging from 45 to 73 years. The older group mean was 78.4 years (SD ± 3.97) with the ages ranging from 74 to 87 years.

Condition	Cronbach's alpha	Measurement error (dB)	Mean SRT_{50} of test 1 (SD) (dB SNR)	Mean SRT_{50} of retest (SD) (dB SNR)
All ears closed aged < 74 (n=30)	0.59	±1.01	-8.1 (±2.0)	-8.6 (±2.7)
All ears closed aged ≥ 74 (n=25)	0.70	±0.91	-8.2 (±2.9)	-8.3 (±2.3)
All ears open aged < 74 (n=29)	0.84	±0.47	-5.6 (±2.5)	-6.1 (±2.3)
All ears open aged ≥ 74 (n=28)	0.78	±0.80	-5.6 (±2.7)	-5.4 (±2.1)

Table 10: Effect of splitting the data set into age groups on the test-retest reliability and variance of the simplified UCAMST in both the open and closed response mode based on two repeated measures.

In the closed condition the test-rest reliability as measured by Cronbach's alpha was higher for the older age group compared to the younger age group. However, the opposite was found for the open condition where the test reliability was higher for the younger age group compared to the older age group. For the open condition the measurement error was smaller for the younger participants compared to the older participants (Refer Table 10).

3.2.5 Effect of degree of hearing loss on the reliability of the simplified UCAMST

To examine the effect the degree of hearing loss had on the reliability of the simplified UCAMST the participants were separated into two groups based on their degree of hearing loss represented by the average of their 500, 1000, 2000 and 4000 Hz pure tone thresholds. This four-frequency average was then classified on the hearing severity scale of Goodman as being a slight, mild, moderate or moderately severe hearing loss. There was only one participant with severe hearing loss based on their four-frequency average and no participants had a profound loss based on this criterion.

The results showed that the measurement error and variance of the SRT_{50} increased with increasing severity of the hearing loss. The internal consistency of the SRT_{50}, as measured by Cronbach's alpha, also increased with increasing hearing loss (Table 11).

Condition	**Cronbach's alpha**	**Measurement error (dB)**	**Mean SRT_{50} of test 1 (SD) (dB SNR)**	**Mean SRT_{50} of retest (SD) (dB SNR)**	**Range in SRT_{50} (dB SNR)**	**Variance in SRT_{50} (dB SNR)**
All slight HL (n=16)	0.67	±0.70	-8.53 (±1.20)	-8.43 (±2.37)	6.1	2.66
All mild HL (n=42)	0.77	±0.80	-7.33 (±2.51)	-7.73 (±2.47)	9.4	5.01
All moderate HL (n=38)	0.78	±0.93	-6.18 (±3.06)	-6.36 (±2.23)	9.8	5.85

All moderately-severe HL (n=14)	0.82	±0.96	-5.13 (±3.12)	-5.69 (±3.84)	12.3	10.4

Table 11: Effect of splitting the data set into hearing ability groups on the test-retest reliability and variance of the simplified UCAMST based on two repeated measures

The mean SRT_{50} increased with increasing severity of hearing loss, showing that participants that had a higher level of hearing loss found it harder to understand speech signal in noise.

3.3 Comparison of means and correlation analysis

Comparison of the means of two groups was carried out by using the paired sample t-test. Correlation analysis was carried out by calculating the Pearson's R values. For the comparison of means and correlation analyses for the simplified UCAMST open vs closed response formats the test and retest datasets were averaged. For the comparison of the simplified UCAMST and the 4-frequency PTA, and the simplified UCAMST and the QuickSIN™ the data from the first trial of the UCAMST was used.

3.3.1 Simplified UCAMST open response mode vs closed response mode

A paired sample t-test was carried out to assess the means of the SRT_{50}s derived from the simplified UCAMST in the open response format vs the closed response format. The results indicated that there is a significant difference at the $p < 0.001$ level between the SRT_{50}s derived from the open vs the closed response formats of the simplified UCAMST, with a mean difference of 2.80 dB SNR. Students t-statistic = 12.5 (df 83) $p < 0.001$, mean difference 2.80 dB, SE difference 0.223 dB. Cohen's d effect size = 1.37 (95% CI 1.07-1.66).

The Pearson correlation coefficient was calculated to ascertain if there was a significant correlation between the SRT_{50}s derived from the open vs the closed response formats of the simplified UCAMST. The results can be seen in Table 12.

		Av SRT_{50} closed	
Av SRT_{50} open	Pearson's r	0.633	***
	p-value	< .001	
	N	84	

*Note, *** p < .001*

Table 12: Results of the Pearson's correlation analysis between the average SRT_{50}s from the open and closed response formats of the simplified UCAMST

The results of the Pearson's correlation showed a significant correlation between the SRT_{50} from the open response mode vs the SRT_{50} from the closed response mode ($r = 0.633$, $p < 0.001$). The coefficient of determination r^2 was calculated for SRT_{50} open vs SRT_{50} closed and indicated that SRT_{50} in the open condition accounts for 40% of the variance of the SRT_{50} in the closed condition.

Any differences in the slopes of the intelligibility function between the open and closed response conditions were also examined. The slope data was found to not meet the assumption of normality that is required to undertake a parametric paired sample t-test (Shapiro-Wilk statistic = 0.743 ($p < 0.001$)). Therefore, a non-parametric Wilcoxon rank test was used to compare the slope data for the open and closed response conditions. The Wilcoxon w test statistic showed that there was a significant average difference between the slopes generated in the open and closed response conditions (w = 631 ($p < 0.001$), mean difference = 0.0375, SE difference = 0.0117, rank biserial correlation effect size = 0.895). On average the open slope values were 3.75%/dB SNR higher than the slopes for the closed response condition. The median slope for the open response condition (n=41) was 12.5 %/dB SNR (± 6.7) and for the closed condition (n=40) was 8.5 %/dB SNR (± 6.2) (Figure 12).

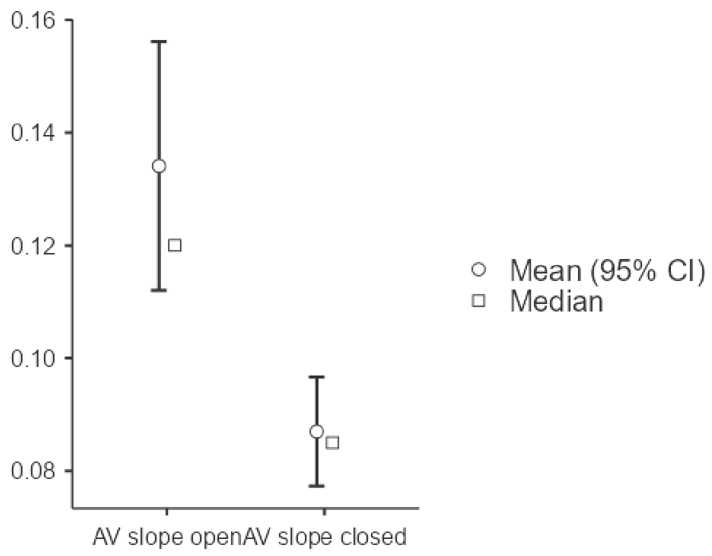


Figure 12: Plot of the mean average slope for the open and the closed-set conditions

3.3.2 Simplified UCAMST vs QuickSIN™

A paired sample t-test was carried out to assess the means of the SRT_{50}s derived from the simplified UCAMST in both the open response and closed response format compared to the SNR loss derived from the monoaural data from the QuickSIN™ test. The results show that there was a significant difference at the $p = < 0.001$ level between the SRT_{50}s derived from both the open and closed response formats of the simplified UCAMST and the SNR loss of the QuickSIN™ (refer Table 13).

The null hypothesis that there was not a significant difference in the SRT_{50} from the simplified UCAMST and the SNR loss from the QuickSIN™ can be rejected. The alternative hypothesis that the mean of the paired differences does not equal zero can be accepted.

Test condition	t-test	df	p	Mean diff	SE diff	Cohen's d	95% CI
QuickSIN™ SNR loss vs UCAMST SRT_{50} open	33.1	110	<.001	16.0	0.48	3.14	2.68-3.58
QuickSIN™ SNR loss vs UCAMST SRT_{50} closed	37.8	110	<.001	18.5	0.49	3.59	3.08-4.09

Table 13: Results of paired samples t-tests between QuickSIN™ SNR loss and the SRT_{50} from the open and closed response formats of the simplified UCAMST.

The Pearson correlation coefficient showed there was a significant correlation between the SRT_{50}s of both the open and the closed response formats of the simplified UCAMST and the SNR loss of the QuickSIN™ at the $p = < 0.001$ level. The results can be seen in Table 14 and Figure 13.

		SRT_{50} Closed	**SRT_{50} Open**
QuickSIN™ loss	Pearson's r	0.552 ***	0.568 ***
	p-value	< .001	< .001
	95% CI Upper	0.669	0.682
	95% CI Lower	0.408	0.426
	N	111	111

Note. *** *p < .001*

Table 14: Results of the Pearson's correlation analysis between the SRT_{50} of the simplified UCAMST and the SNR loss of the QuickSIN™

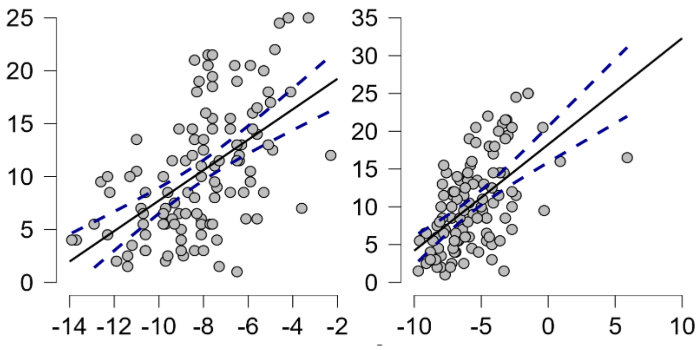


Figure 13: Correlation plots of QuickSIN™ loss (y-axis) vs SRT_{50} in the closed format (left panel) and the open format (right panel) condition. The blue dotted line represents the 95% CI.

The coefficient of determination r^2 was calculated for SRT_{50} open from the simplified UCAMST and SNR loss from the QuickSIN™, which indicated that SRT_{50} in the open condition accounts for 32% of the variance of the SRN loss in the QuickSIN™. The coefficient of determination between SRT_{50} closed from the simplified UCAMST vs QuickSIN™ SNR loss indicated that SRT_{50} closed from the simplified UCAMST accounted for 30% of the variance of the QuickSIN™ SNR loss.

3.3.3 Simplified UCAMST vs age

To assess if age is significantly correlated with SNR at which SRT_{50} is estimated for the simplified UCAMST a Pearson's r value was calculated. The results are shown in table 15.

The results show that age of the participant was not associated with their SRT_{50} obtained using the simplified UCASMT in the closed response format. However, there is a positive correlation at the $p < 0.05$ level between the participants age and their SRT_{50} obtained using the simplified UCASMT in the open response format. The coefficient of determination indicated that age only accounted for 7% of the variation in the SRT_{50} in the open response format.

		Participant Age
Av SRT_{50} closed	Pearson's r	0.106
	p-value	0.339
	N	84
Av SRT_{50} open	Pearson's r	0.271 *
	p-value	0.012
	N	84

*Note. * $p < .05$*

Table 15: Results of the Pearson's correlation analysis between the participants age and their SRT_{50} obtained from the simplified UCAMST.

A partial correlation analysis was also undertaken between age and SRT_{50} in both the open and closed conditions, while controlling for the 4-frequency pure tone average of the participant (Table 16). This analysis showed no correlation between age and SRT_{50} in either response condition when the 4-frequency pure tone average was controlled for.

		Av SRT_{50} closed	Av SRT_{50} open
Age	Pearson's r	0.024	0.180
	p-value	0.865	0.183
	N	55	57

Note. controlling for '4FA'

Table 16: Results of the partial Pearson's correlation analysis between the participants age and their SRT_{50} while controlling for the participants 4-frequency PTA average (4FA) obtained from the simplified UCAMST.

3.3.4 Simplified UCAMST vs pure tone average hearing thresholds

To assess if a participant's pure tone average hearing threshold is significantly correlated with their SRT_{50} obtained with the simplified UCAMST a Pearson's r value was calculated (Table 17 & Figure 14). The participants PTA hearing threshold was based on the average of the 4 frequencies (4FA) 500, 1000, 2000 and 4000 Hz.

		RE SRT_{50} Open	**LE SRT_{50} Open**	**RE SRT_{50} Closed**	**LE SRT_{50} Closed**	**RE 4FA**
RE 4FA	Pearson's r	0.750 ***	0.635 ***	0.580 ***	0.692 ***	—
	p-value	< .001	< .001	< .001	< .001	—
	95% CI Upper	0.843	0.765	0.726	0.804	—
	95% CI Lower	0.615	0.456	0.384	0.533	—
	N	61	61	61	61	—
LE 4FA	Pearson's r	0.742 ***	0.680 ***	0.525 ***	0.684 ***	0.845 ***
	p-value	< .001	< .001	< .001	< .001	< .001
	95% CI Upper	0.837	0.795	0.687	0.798	0.904
	95% CI Lower	0.602	0.516	0.316	0.521	0.754
	N	61	61	61	61	61

Note. *** $p < .001$

Table 17: Results of the Pearson's correlation analysis between the participants 4 frequency pure tone average and their SRT_{50} obtained from the simplified UCAMST.

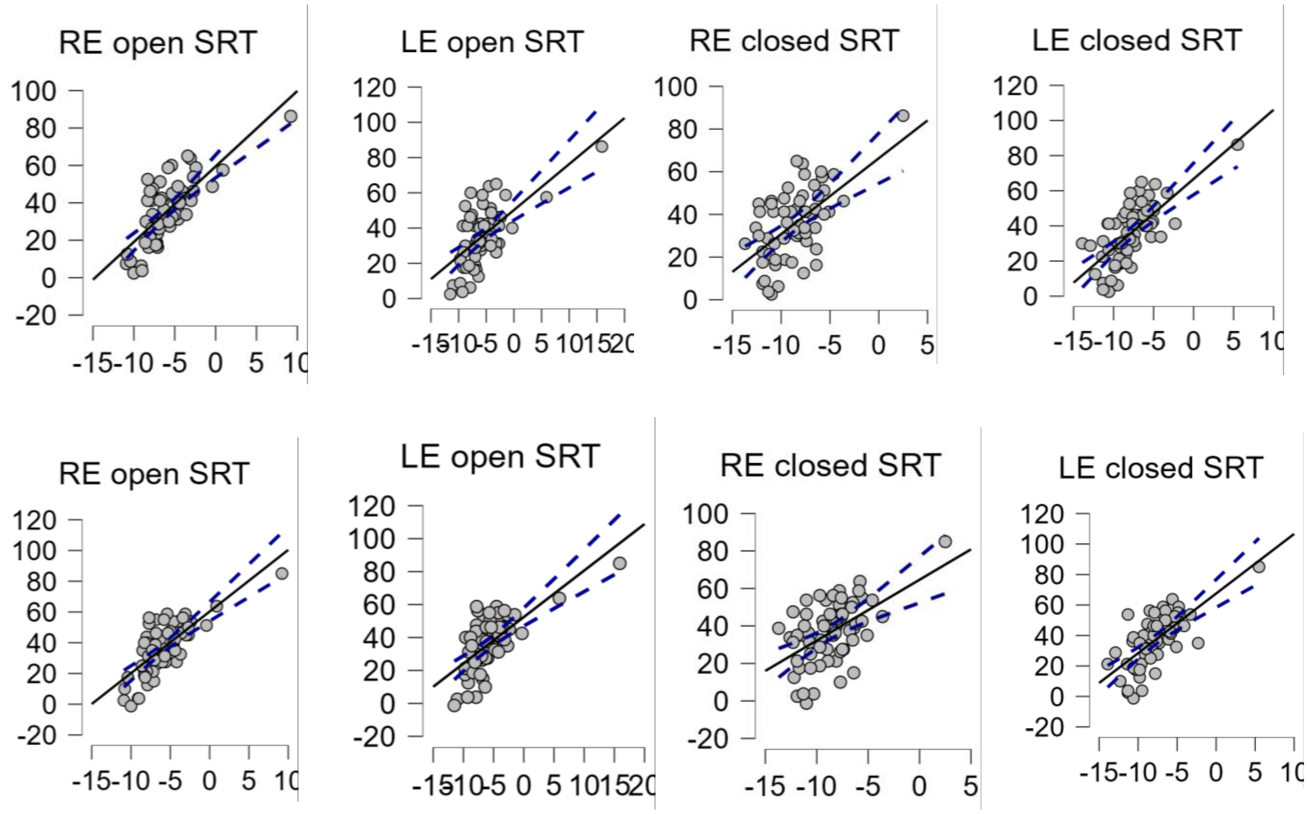


Figure 14: Correlation plots of the 4-Frequency Average (y-axis) vs SRT_{50} (x-axis) in the closed and open formats. The top panel represents the 4FA of the right ear and the bottom panel represents the 4FA of the left ear. The solid grey line represents the Pearson's r value, and the blue dotted line represents the 95% CI.

The correlation analysis showed that there was a significant correlation at the $p < .001$ level between a participant's pure tone average of the 4 frequencies at 500, 1000, 2000 and 4000 Hz and their SRT_{50} derived from the simplified UCAMST in both the open and closed response format. The stronger correlation was between the SRT_{50} from the open response condition and the participants 4 frequency pure tone average.

The coefficient of determination r^2 indicated that the participants 4 frequency pure tone average accounted for 56% of the variation in a participants SRT_{50} for the open response format in the right ear, and 46% of the variation in the left ear. For the closed response format, the 4-frequency average accounted for 34% of the variation in a participants SRT_{50} for their right ear and 48% for their left ear.

A partial correlation analysis was also undertaken between the four-frequency average and SRT_{50} in both the open and closed conditions, while controlling for the age of the participant (Table 18). This analysis showed that even though the Pearson's r value decreased when age was controlled for, the correlation between the participants four-frequency pure tone average and their SRT_{50} in both the open and closed condition was still significantly correlated at the $p = <0.001$ level.

		RE Open SRT_{50}	**LE Open SRT_{50}**	**RE SRT Closed**	**LE SRT Closed**	**Right 4FA**
Right 4FA	Pearson's r	0.689 ***	0.533 ***	0.506 ***	0.639 ***	—
	p-value	< .001	< .001	< .001	< .001	—
	N	61	61	61	61	—
Left 4FA	Pearson's r	0.678 ***	0.592 ***	0.438 ***	0.628 ***	0.775 ***
	p-value	< .001	< .001	< .001	< .001	< .001
	N	61	61	61	61	61

Note. controlling for 'Age' Note. *** p < .001

Table 18: Results of the partial Pearson's correlation analysis between the participants four-frequency pure tone average and their SRT_{50} while controlling for the participants age obtained from the simplified UCAMST.

3.3.5 Simplified UCAMST vs Mini-ACE score

A Pearson's r value was calculated to ascertain if the score on the Mini-ACE cognitive test is correlated with the SRT_{50}s derived from the simplified UCAMST (Table 19).

		Mini-ACE
Av SRT_{50} open	Pearson's r	-0.305 *
	p-value	0.025
	95% CI Upper	-0.040
	95% CI Lower	-0.529
	N	54
Av SRT_{50} closed	Pearson's r	-0.221
	p-value	0.109
	95% CI Upper	0.050
	95% CI Lower	-0.461
	N	54

Note. * p < .05

Table 19: Results of the Pearson's correlation analysis between the participants score on the Mini-ACE and their SRT_{50} obtained from the simplified UCAMST.

The correlation analysis showed that there was a significant correlation at the $p < 0.05$ level between a participant's score on the Mini-ACE and their SRT_{50} derived from the simplified UCAMST in the open response format. There was no significant correlation between the participants score on the Mini-ACE and their SRT_{50} derived from the simplified UCAMST in the closed response format.

The coefficient of determination r^2 indicated that the participants score on the Mini-ACE accounted for 9% of the variation in a participants SRT_{50} in the open response format.

Discussion

4.1 Introduction

In current clinical practice, hearing loss is diagnosed mainly on the basis of pure-tone audiometry and speech testing in quiet. However, pure-tone audiometry only assesses the sensitivity to simple pure tones in quiet which is not related to the ability to hear complex speech and environmental sounds at supra-threshold sound pressure levels. Additionally, whilst speech testing in quiet can provide some information about supra-threshold deficits, it provides no information about audibility, frequency selectivity and temporal processing acuity in background noise, which are important for speech understanding in the real world where background noise is a factor. Speech testing in noise has the highest validity in assessing additional, important aspects of hearing impairment beyond that provided by the audiogram and speech testing in quiet to give a more accurate characterization of a listener's hearing ability and potential deficits.

The simplified UCAMST is designed to test the ability to perceive and understand speech in background noise, which has high face validity as this is the most common complaint of a subject with hearing loss. Whilst the simplified UCAMST was originally designed to test paediatric populations we hypothesis that it may be suitable to test older populations with hearing loss, especially those with cognitive deficits. Up until this study the simplified UCAMST had not been used to test adults with hearing impairment, only normative data with hearing impaired paediatric populations had been collected.

4.2 The simplified UCAMST and the testing of adults

Until this study the simplified UCAMST had not been used to test adults with hearing loss, having only being piloted on adults with normal hearing (Jenkins-Foreman, 2018;

Taylor 2021). Data from normal hearing adults generated a mean SRT_{50} in the closed response condition of -11.7 dB SNR and a mean SRT_{50} of -9.6 dB SNR in the open condition (Taylor, 2021). These values are approximately 1 dB lower than those obtained for normal hearing ears in the present study (-10.7 ± 1.9 dB SNR and -8.6 ± 2.0 dB SNR for closed-set and open-set respectively).

The present study of hearing-impaired adults generated a SRT_{50} mean of -8.32 (SD ± 2.47) dB SNR in the closed condition and a mean SRT_{50} of -5.67 (SD ±2.38) dB SNR in the open condition. Therefore, the present study showed that adults with hearing loss had a poorer performance (higher SRT values) in comparison to that of normal hearing adults.

Previous research has shown that there is no significant differences between the simplified UCAMST sentence lists that are presented to listeners in either the open set ($F(15,109) = 1.491$, $p = 0.116$, partial eta-squared = 0.135) or closed set conditions ($F(15, 26) = 0.567$, $p = 0.896$, partial eta-squared = 0.055) (Taylor, 2021). The inter-list standard deviation of ± 1.7 dB SNR for both the open and closed set conditions (Taylor, 2021) was smaller than the inter-subject standard deviation found in the present study group (± 2.2 dB SNR for the open condition and ± 2.1 dB SNR for the closed condition). Therefore, the differences between speech lists presented are smaller than between subjects.

Taken together, all these results indicate that the simplified UCAMST has the power to differentiate between adults with normal hearing and those adults with a hearing loss.

4.2.1 Test-retest reliability of the simplified UCASMT for the testing of adults

The test-retest reliability ascertains if a measured difference in speech in noise intelligibility, represented by the SRT_{50} represents a significant difference in performance level (Vas, 2013; Weir, 2005). Fewer measurements are needed to detect a clinically significant difference in SRT_{50} if the test-retest reliability is smaller. Therefore, the test-retest reliability is a measure of clinical efficiency, and a high degree of test-retest reliability is critical in order to obtain accurate and reliable speech recognition measurements in noise as the differences between normal hearing- and hearing-impaired subjects are relatively small.

For the simplified UCAMST we would expect a small within-subject variability as the speech material is highly homogenous in terms of intelligibility. A lot of research has previously been undertaken on the simplified UCAMST to ensure all the scorable speech lists presented to the subject are of equal intelligibility (Jenkins-Forman, 2019; Taylor 2021). With the knowledge that the speech lists in the simplified UCAMST are not a source of variation in the test results we can analyse the test-retest reliability between subjects.

The test-retest error measurement most often used in the literature to assess matrix sentence tests, was also used in this study so comparisons with any published data on other matrix sentence tests could be made. The test-retest measurement of error is calculated as the root mean square of the within-subject standard deviations of repeated measures of SRTs. The test-retest measurement error for all participants in the closed response format of the simplified UCAMST was 0.96 dB SNR and for the open response format was 0.75 dB SNR. Having a test-retest error measurement of less than 1 dB means the test is a very reliable method of ascertaining a listener’s ability to perceive speech in noise. Especially considering pure tone audiometry and other speech perception test protocols work in step sizes of 5 dB.

The reliability results of the simplified UCAMST from this study are comparable to published reliability data of other simplified speech matrix tests. Puglisi and colleagues (2021) looked at the simplified Italian matrix, known as the siIMAX test, in the open format and reported it had a reliability of 1 dB in determining the SRT_{50}. The study of Puglisi was carried out with 20 subjects that all had average pure tone thresholds of less than 20 dB HL.

In comparison, the present study used a much more variable population of hearing-impaired subjects. Another recent study by Willberg et al. (2020) also used normal hearing subjects to test the reliability of a simplified matrix sentence test, in this study the Finnish version. This study tested 20 subjects with pure tone thresholds less than 15 dB HL and found the test - retest reliability measure for SRT_{50} was 0.8 dB. The only published data on the reliability of testing hearing impaired adults with a simplified matrix test was also for the Finnish version of the test. Sixteen hearing impaired subjects with a mean pure tone threshold of 42 dB HL gave a test-retest error measurement of 1.3 dB (Willberg et al., 2020).

The studies described above using normal hearing subjects did not have the potential cofounding factor of hearing loss or older age as they were carried out on normal hearing younger adults with a mean age of 24.5 (Puglisi et al, 2021) and 25.4 years (Willberg et al., 2020). In comparison, the present study and the study of hearing-impaired subjects by Willberg et al, (2020) were based on older adults, with both studies having a mean participant age of 69 years.

4.2.2 Open vs closed format response of the simplified UCAMST and the SRT_{50}

This study established differences in performance, represented by the SRT_{50}, between the open and closed response format of the simplified UCAMST. The open response format was found to be more reliable than the closed format response format if reliability was measured by the Cronbach's alpha statistic. However, the closed response format had a smaller measurement error than the open response format as discussed above.

When the mean SRT_{50} of the open and closed conditions are examined, the results show the mean SRT_{50} derived from the open condition (-5.91 dB SNR ± 2.26) was higher than the mean SRT_{50} from the closed response condition (-8.67 dB SNR ± 2.31), indicating participants required a 2.8 dB better SNR to respond correctly in the open-set condition. The difference in the SRT_{50} values derived from the open vs the closed format is significant (Students t-statistic = 12.5 (df 83) p = <0.00) with a Cohen's d effect size of 1.37 (95% CI 1.07-1.66).

It had previously been established using normal hearing subjects that the simplified UCAMST also resulted in higher SRT_{50}s in the open response condition compared to the closed condition (Jenkins-Foreman, 2018; Taylor, 2021). This same finding in the present study reinforces the fact that the open and closed response formats of the simplified UCAMST cannot be used interchangeably without accounting for offsets in the two scores.

Published studies on other matrix sentence tests have also found the SRT_{50} improves when the test is conducted in the closed format rather than the open format. However, the improvement seen has not been as large as the 2.8 dB SNR seen in this study. For example, when the Spanish (Hochmuth et al., 2012), Italian (Puglisi et al., 2015), Russian (Warzybok et al., 2015) and Mandarin Chinese (Hu et al., 2018) matrix sentence tests were used in the closed response format there was an improvement of only approximately 0.8 dB SNR compared to the open response format. It must be noted however that these studies all compared the larger 50-word matrix test formats in the open and closed conditions, rather than the smaller simplified 18-word matrix format used in this study. These results are thought to reflect the advantage of having the word matrix as a visual cue to narrow down the possible correct response, in the closed response format. Having a visual aid of the possible alternative words heard helps the listener make better educated guesses when intelligibility is poor (Theelen–van den Hoek et al., 2014). We can hypotheses that the larger improvement seen for the closed format in this study may be due to the smaller size of the word matrix used as a visual cue, enabling the subjects to be able to search and select the correct word they heard quicker and more accurately than they could with a larger 50-word matrix.

The Polish matrix sentence test found no significant differences between the open and closed conditions, however in this study the subjects underwent extensive hour-long training sessions until the SRT_{50} became stable before it was measured (Ozimek et al., 2010). It is not practical to have such extensive training in a clinical setting where time is limited. Therefore, we can conclude that the open and closed conditions of the simplified UCAMST cannot be used interchangeably, the presentation mode needs to be chosen before the test is conducted, and scores obtained with the simplified UCAMST can only be directly compared to scores obtained using the same response method.

4.2.3 Open vs closed format response of the simplified UCAMST and the slope

The average slope of the speech intelligibility functions gives information about the accuracy of the SRT estimates, and the sensitivity of the test (Theunissen et al., 2009). A steeper slope gives a more accurate and efficient estimate of SRT_{50}, as small changes in the SNR give rise to larger changes in the performance of a listener (MacPherson and Akeroyd, 2014; Ozimek et al., 2010).

The median slope found in the present study was 12.5 %/dB SNR (± 6.7) for the open condition and 8.5 %/dB SNR (± 6.2) for the closed condition. So, the closed condition slope was shallower, and therefore predicts SRT less accurately than the slope of the open condition.

Studies have also shown that slopes are shallower for listeners with a hearing impairment compared to normal hearing listeners (Dietz et al. 2015; Hey et al. 2014; Smits & Festen, 2011). A consequence of the shallower slopes with increasing hearing loss is that the measurement error in SRT scores also increases (Smits & Festen, 2011).

4.2.4 Age and the simplified UCAMST

Increasing age has been shown to correlate with increasing difficulty in recognising speech signals in noise (Dubno, 2015; Goossens et al., 2017; Helfer et al., 2017; Souza et al., 2007). In the present study an increased measurement error was seen with increasing age in the open condition, increasing from ± 0.47 in the younger age group (< 74 years) to ± 0.80 in the older age group (≥ 74 years). Additionally, a decrease in the Cronbach alpha reliability measure was seen in the open condition, decreasing from 0.84 in the younger group to 0.78 in the older group. It is hypothesized that this increase in measurement error and decrease in reliability in the open condition with increasing age is due to increasing hearing loss and declining cognitive function with older age and the absence of the visual cue of the word matrix having a greater effect with increased age.

A significant, but small positive correlation was seen between age and SRT_{50} for the open condition ($r = 0.271$, $p<0.05$). The same trend was not seen in the closed condition.

We may expect that older participants would give less reliable SRT_{50} scores as age is a variable related to performance in speech in noise tests, even when audiometric factors have been controlled for in the study design or statistically (Working group on speech understanding and aging, 1988; Walden & Walden, 2004). To investigate this further, partial correlation analyses between age and SRT_{50} while controlling for pure tone thresholds were conducted. However, no significant influence of age on the SRT_{50} when pure tone thresholds were controlled for was seen. An influence of age on the SRT_{50} independent of the effect of pure tone threshold has been shown in other matrix sentence tests. However, the relationship is often weak (Warzybok et al., 2020).

These results indicate that the SRT_{50} of the simplified UCAMST more strongly reflects supra-threshold deficits in the auditory system, rather than just age-related changes in audibility (Lee et al., 2016; Mukari et al., 2020; Zanto et al., 2010). Moreover, in this study the hearing loss of a subject mediated the effect of age on their speech in noise performance, with the subjects chronological age having no significant effect.

4.2.5 Cognitive status and the simplified UCAMST

There is a lot of research suggesting that differences in cognitive abilities, such as working memory, contribute to poorer performance in recognising and understanding speech in noise, especially for older adults (Akeroyd, 2008; Castiglione et al., 2009; Diao et al., 2021; Dryden et al., 2017).

The present study showed that there was an effect of cognitive status on the reliability of the SRT_{50} estimate and the test measurement error. The Cronbach alpha as a measure of reliability increased for both the open and closed condition when participants that did not pass the Mini-ACE cognitive screen were removed from the dataset. Additionally, the test measurement error of the SRT_{50} in the open condition decreased significantly from ± 0.75 to ± 0.35 dB when participants who had failed the cognitive screen were removed from the dataset.

The scores on the Mini-ACE and the SRT_{50}s in the open condition were significantly negatively correlated ($r = -0.305$, $p < 0.05$). So, when the participant had a worse score (i.e., lower score) on the Mini-ACE cognitive screen they tended to have a have a worse SRT_{50} (i.e., higher SRT_{50}). Interestingly, when Dryden et al. (2017) reviewed the literature, they found that most published studies had found the same magnitude of correlation as found in this study ($r = 0.3$) between cognitive performance and speech in noise perception. There was also very little variation in the association between cognition and speech in noise performance across the different cognitive subdomains, such as attention, memory, executive function, IQ and processing speed when sentences were used as the target speech stimuli (Dryden et al., 2017).

These results indicate that due to the higher cognitive load associated with speech tests, such as the simplified UCAMST that use sentence stimuli, there is a need to consider the role of an individual's cognitive status in their SRT estimation (Cervera et al., 2009; McArdle et al., 2005; Wilson et al., 2007). The present study indicates this is true in the open response condition, but not such a factor in the closed response condition, where the listener has access to the word matrix.

4.2.6 Pure tone thresholds and the simplified UCAMST

When the data was broken down into hearing loss groups according to the Goodman classification of hearing severity scale, it clearly showed that the range and variability of the SRT_{50} scores increased with increasing levels of hearing loss. The range and variance in the participants with a slight hearing loss was 6.1 and 2.7 dB SNR respectively. These values increased to 12.3 dB SNR (range) and 10.4 dB SNR (variance) for participants that had a moderately severe hearing loss.

The variability of the SRT_{50} increasing with increasing levels of hearing loss clearly indicates that an individual's ability to hear speech in noise cannot be predicted based on their puretone thresholds, as has also been shown in other studies (Kollmeier et al., 2016; Plomp, 1978; Wardenga et al., 2015). This highlights why it so important to include a speech test in noise in the clinical testing battery as the most common complaint of people with hearing loss is their difficulty in following conversation in a noisy situation. Speech in noise tests, such as the simplified UCAMST assess not only the sensitivity of the auditory system (as pure tone testing does) but also assess suprathreshold deficits (Grant and Walden 2013; Kollmeier et al. 2016; Plomp 1978).

Matrix sentence tests in alternative languages have shown the same trend of increasing SRT_{50} scores associated with increasing pure tone thresholds. However, the nature of the relationship does vary. Data from the German matrix sentence test showed the SRT_{50} increased at different rates based on the subjects hearing level (Wardenga et al., 2015). For example, subjects with a mild and moderate hearing loss showed a slow SRT_{50} increase of 1.5 dB SNR for every 10 dB HL increase in pure tone threshold, but a much steeper SRT_{50} increase of 8 dB SNR per 10 dB HL in subjects with a severe hearing loss. The present study does not show this relationship as the increase in SRT_{50} was comparable across subjects with different degrees of hearing loss. For example, the increase in SRT_{50} between subjects with a slight hearing loss and a mild hearing loss was 1.0 dB SNR for a 13 dB HL increase in hearing loss, and the increase in SRT_{50} between subjects with a moderate and moderately severe hearing loss was 0.9 dB SNR for a 14 dB HL difference in hearing level. The same comparable SRT_{50} increase across subjects with different degrees of hearing loss as seen in this study was also seen in the Russian matrix test (Warzybok et al., 2020).

4.3 Comparison of the simplified UCAMST and the QuickSIN™ test

The QuickSIN™ test was carried out on all study participants so that the results of another sentence-level speech-in-noise test could be compared to the results of the simplified UCAMST. In the validation phase of a new MST comparisons with other speech tests is important to help ensure comparability across other speech assessments (Akeroyd et al., 2015).

The QuickSIN™ test was chosen as the comparison test as it is the most used speech-in-noise test used in the NZ clinical setting due to its ability to calculate an individual's SRT using clinical time efficiently. However, speech-in-noise testing is still not commonly used in NZ audiology clinics as part of the routine clinical battery.

Only a few studies have compared two different sentence-level speech-in-noise tests in the same hearing impaired sample group as this study has done (Dillon et al., 2016; Jansen et al., 2012; Wilson et al., 2007; Willberg et al., 2021). The study by Dillon et al. (2016) demonstrated how differences in test-specific characteristics, such as the type of noise used and the length and complexity of the sentences, gives rise to significantly different speech recognition results even when testing the same sample group. The QuickSIN™ test which was used in the current study uses four-talker babble speech noise in American English at a fixed level (70 dB HL, 85 dB SPL) in comparison to the steady-state speech shaped noise at a fixed level (50 dB HL, 65 dB SPL) used in the simplified UCAMST. Additionally, the QuickSIN™ test uses longer and more complex sentences than the short simple pseudo-sentences of the simplified UCAMST. Despite these differences between the two tests, we found a statistically significant correlation at the $p < 0.001$ level between the SRT_{50} of the simplified UCAMST and the SNR loss of the QuickSIN™. This is an important indication of the validity of the simplified UCAMST, the test is measuring what we think it is and the results are comparable to the results from another speech in noise test that is in clinical use.

The QuickSIN™ test scored higher than the simplified UCAMST on the Cronbach's alpha measure of reliability, however the test-retest measurement error was higher than the simplified UCAMST. The mean test-retest measurement error for the QuickSIN™ was ± 1.4 dB while the measurement was ± 0.96 dB for the open condition and ± 0.75 dB for the closed condition of the simplified UCAMST. The fact that the simplified UCAMST can give more reliable results, as measured by the test-retest measurement error, than the commercially available and clinically accepted QuickSIN™ is encouraging for the clinical acceptance of the simplified UCAMST.

The time taken to perform the QuickSIN™ for both ears is approximately 6 minutes (two practice lists, followed by two test lists per ear, taking approximately 1 minute per list). Across the present wider study (including both testing in noise and in quiet, n=769), the time taken for each simplified UCAMST was 4 minutes 36 seconds (± 36 seconds) for each ear. The Brand and Kollmeier A2 procedure used in the simplified UCAMST for this study presented 30 pseudo-sentences to obtain both an estimate of SRT and slope. However, if only the SRT was of interest, a 20-trial A1 procedure could be used instead (Brand & Kollmeier, 2002). This procedure requires 10 fewer trials, thereby reducing the test time to just over 3 minutes (3 minutes, 4 seconds) per ear. With the addition of two practice lists the total test time would be approximately 12 minutes. So, whilst the simplified UCAMST is not as clinically efficient as the QuickSIN™ there are many other advantages of incorporating the simplified UCAMST over the QuickSIN™ into the clinical test battery. These advantages being that the simplified UCAMST has a lower measurement error, is specific for NZ English speakers, has a higher face-validity and the test can also be used in an auditory-visual mode to test auditory-visual integration.

4.4 Limitations of this study and future research

Although every effort was made to maintain scientific rigor in the current study, constraints on the experimental design due to time and methodology constraints meant that there are limitations of the current study which may have influenced the findings. These will be examined in the following sections to allow for impartial interpretation of the results of this study and to guide future studies on the simplified UCAMST.

4.4.1 Age of the participants

The age range of the current study was skewed towards older adults, with a mean age of participants tested in the open condition of 72.1 years (SD ± 8.4) and in the closed condition of 70.0 years (SD ± 9.81). To see the true effect of age on the reliability of the simplified UCAMST a greater spread of ages, including younger adults would be more appropriate. It has been shown that the relevance of age as a predictor is strongly dependant on the age distribution of the study group (Houtgast & Festen, 2008). Some studies that include a wide range of ages have shown significant correlations between age and speech in noise performance even after controlling for the listeners pure tone average (Helfer et al., 2017; Houtgast & Festen, 2008).

However, to get younger adults with the same degree of high frequency sloping hearing loss as represented in this study is very difficult as this pattern of hearing loss is mostly associated with aging of the auditory system. Additionally, there is more evidence accumulating that age by itself is not the essential factor but is a proxy measure for the deficits in the functions and processes of the auditory system that occur with age. When all the variables important to speech in noise perception are known and modelled age may no longer be a predictor variable (Houtgast et al., 2008).

4.4.2 Comparison of the simplified UCAMST with the full version UCAMST

Direct comparisons between results obtained with the simplified UCAMST and the full version of the UCAMST with the same test population would have been beneficial. Testing the same population of older hearing-impaired adults would allow a direct comparison of individual SRT_{50} values obtained with the UCAMST and the simplified

UCAMST to ascertain if the simplified version of the test is more accurate and/or reliable for some adults. We hypothesise that groups of adults who may have one or more of the following, a level of cognitive impairment, a more severe hearing impairment and/or just advanced age may perform better on the simplified version of the UCAMST over the full version.

The intelligibility of the individual words is the same in the full version of the UCAMST and the simplified version. Therefore, we could assume that any improvement in SRT_{50} scores seen with the simplified UCAMST would be due to the shorter and less cognitively demanding test material and procedure of the simplified UMASMT.

However, with this research study the testing procedure involving different conditions was already long and cognitively demanding, so it wasn't feasible to include the longer UCAMST testing as well. Additionally, in normal hearing subjects there is good data that the two versions of the test don't give statistically different results (Jenkins-Forman, 2018; Taylor, 2020). However, it is not known if hearing-impaired adults give significantly different results on the two versions of the UCAMST.

4.4.3 Comparison with the QuickSIN™ and other speech in noise tests

Too ensure the validity of the simplified UCAMST test construct it is important to assess the correlation between the test's SRT_{50} with SRT_{50}s from other tests that test performance in speech in noise (Theunissen et al., 2019). However, there are no other established tests in NZ English that assess speech in noise performance. Therefore, it was necessary to test the performance against the most used speech in noise test in NZ, the QuickSIN™. However, using the QuickSIN™ as the comparison test has its limitations as it uses an American talker which can cause dialect and accent confusions for native NZ English speakers and lead to erroneous SRT_{50} scores (van Wijingaarden et al., 2002; Zokoll et al., 2013).

4.4.4 Comparison of speech in noise reception and cognition

Although this study and published studies have found a correlation between speech in noise perception and performance on a cognitive test, no single cognitive test produces reliable correlations. The cognitive screening test used in this study, the Mini-ACE has been developed for clinical application but is non-specific in terms of what cognitive domains are being tested, so impaired performance could be due to several cognitive mechanisms.

It is known that to successfully understand speech in noise the listener must successfully group the bits of the acoustic signal that belong to the target speech, hold their attention on these speech elements and commit them to their short-term working auditory working memory (Akeroyd, 2008; Heinrich et al., 2015; Lad et al., 2020). While the Mini-Ace test is a general screening test for mild cognitive impairment and dementia it does contain elements that test attention and short-term working memory and recall (Hsieh et al., 2015). However, there is a chance that the Mini-ACE is not sensitive enough to measure subtle differences in cognitive functioning that affects speech discrimination. Future research on the effect of cognitive status on the simplified UCAMST should consider employing additional cognitive measures, including tasks of auditory working memory.

Focusing attention is also an important predictive factor in speech in noise performance (Oberfeld & Klockner-Nowotny, 2016). Some speech in noise tests use cues before the presentation of the speech stimuli to prime the listener to focus their attention in time. For example, the word “ready” is spoken before the start of the presentation of the speech stimuli in the BKB-SIN sentence test (Etymotic Research, 2005). In future iterations of the UCAMST it may be worth considering the inclusion of a cue before the presentation of the sentence to see what effect it has on the speech in noise performance.

4.4.5 Testing protocol

For subjects with a hearing loss the presence of background noise is a much more taxing listening condition for them, compared to those with normal hearing and compared to a listening situation with no background noise. Those with a hearing loss must exert a much higher level of listening effort and concentration to understand speech in noise, resulting in greater fatigue (Krueger et al., 2017). Furthermore, older adults with a hearing loss have to expend more listening effort, involving attention and cognitive resources, than younger adults to understanding speech in noise (Gosselin & Gagné, 2011; Tun & Wingfield, 2009). Therefore, a high clinical efficiency of testing is especially important for application of MST in noise in hearing-impaired and older listeners.

The testing session for the present study lasted approximately two and a half hours and many of the study participants expressed fatigue during the measurement session and requested a break or took up our suggestion of a break when it was offered. Fatigue can affect the performance on speech in noise tests (Theelen–van den Hoek, 2014). However, any effects of cognitive fatigue did not appear to have a significant impact on the mean SRT_{50} test and retest scores as no significant differences were found between the SRT_{50} scores for the first test and the retest for any condition. The retest took place right at the end of the testing session. Even the group of participants that failed the mini-ACE, and so were likely to have some mild cognitive impairment, did not show a significant difference between SRT_{50} for test one and the retest ($t (25) = 1.64$, $p = 0.113$, mean difference = 0.669. SE difference = 0.407, Cohen's d effect size = 0.322 (CI = -0.0754 – 0.714). It also must be noted that in a real-life clinical application of the simplified UCAMST the test procedure would be a lot shorter.

4.5 Concluding remarks

This research is the part of a continuing effort to develop and validate a simplified matrix sentence test for use in audiology clinics in NZ. This study focused on validating the usefulness of using the simplified version of the UCAMST that was originally developed to test paediatric populations, to test older adults who may also have cognitive impairment alongside their hearing impairment. With the majority of people utilising audiological services being over the age of 65 years in NZ, the need for accurate and efficient measures of speech performance in noise for this age group is paramount. Age related high frequency hearing loss in NZ is currently quantified using only pure tone audiometry and speech in quiet testing which does not capture the difficulties older adults experience with hearing in speech in noise and the effects of neural hearing loss. Ultimately it leads to underestimation of the relationship between hearing loss and cognitive decline and the full effect of everyday communication difficulties. Utilising speech in noise tests in the clinical work-up can provide this missing information.

The present study found that the simplified UCAMST can give a reliable indication of an adult listeners understanding of speech in noise. While the simplified UCAMST with its shorter test procedure and fewer test items was originally intended for the testing of paediatric populations the current study shows that it is also reliable enough for testing of older adults with hearing loss as well. This study is an important step towards the ultimate goal of integration of the simplified UCAMST within the NZ audiological test battery.

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Appendix A

Ethics approval

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE
Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2021/41/LR

26 August 2021

Cynthia McGill and Natalie Kerr

School of Psychology, Speech and Hearing

UNIVERSITY OF CANTERBURY

Dear Cynthia and Natalie

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Impact of Working Memory on Performance of Matrix Sentence Tests in Quiet and in Noise".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 20th August 2021.

With best wishes for your project.

Yours sincerely

Dr Dean Sutherland

Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. **www.canterbury.ac.nz**

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HUMAN ETHICS COMMITTEE
Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2021/41/LR Amendment 1

28 September 2021

Cynthia McGill and Natalie Kerr

School of Psychology, Speech and Hearing

UNIVERSITY OF CANTERBURY

Dear Cynthia and Natalie

Thank you for your request for an amendment to your research proposal "Impact of Working Memory on Performance of Matrix Sentence Tests in Quiet and in Noise" as outlined in your email dated 22nd September 2021.

I am pleased to advise that this request has been considered and approved by the Human Ethics Committee.

Yours sincerely

Dr Dean Sutherland

Chair, Human Ethics Committee

University of Canterbury Private Bag 4800, Christchurch 8140, New Zealand. **www.canterbury.ac.nz**

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Appendix B

Information sheet for research participants

Information Sheet

Natalie Kerr and Cynthia McGill
Master of Audiology students
Te Kura Mahi ā-Hirikapo | School of Psychology, Speech and Hearing
natalie.kerr@pg.canterbury.ac.nz; cynthia.mcgill@pg.canterbury.ac.nz

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- *The purpose of this information sheet is to inform you about this project so you can decide whether you want to take part.*
- *It is important that you understand this information. Take as much time as you need to decide.*
- *Feel free to talk about your participation in this project with your family or health care providers.*

Assessment of the reliability of a simplified matrix sentence test in quiet and in noise.

Our purpose

- The aim of our project is to look at how reliable a new simplified matrix sentence test is in determining how well you understand speech both in quiet and in noise.

<u>What is involved?</u>

- If you choose to take part, we will ask you to take a traditional hearing test and a speech test, both in quiet and in noise. We will also test your cognition. Total time of testing is approximately 120 minutes. Please see the next page for details of each test
- This will be done at the University of Canterbury Speech and Hearing Clinic.
- The hearing tests and hearing screenings are free, and you will receive a $20 voucher as an acknowledgement of your participation in this study.

<u>Who is eligible for the project?</u>

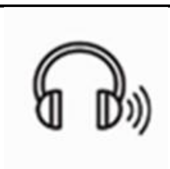
- People who:
- Are 18 years of age or older
- Are a native speaker of NZ English
- Have normal hearing or a hearing impairment (in one or both ears)
- Have no current middle ear pathology (i.e. ear infection)

<u>What will I do if I take part?</u>

As mentioned above, there are three main parts to the testing session, and each part takes about 30 mins.

<u>The hearing test</u>

	We will ask you some questions about your general health, your hearing and balance. The answers to these questions help us to understand what difficulties you may be having. We want to know: if you have any problems with your hearing, balance, or communication, when these problems started.
	We check the outside of your ears. Then we will use a bright light to look at the inside of your ears. This helps us to make sure your ears are healthy inside and out and clear of wax.
	We will then measure how your ears react to sound and pressure changes.

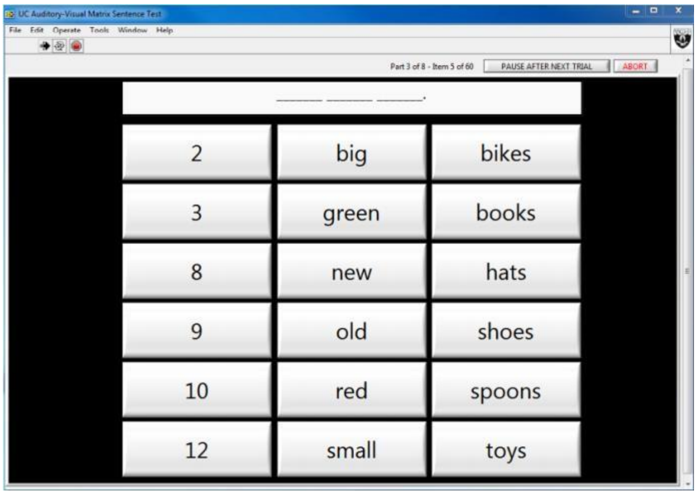
	This test tells us if your eardrum, ear bones, and muscles are moving as they should.
	We will fit earphones on or in your ears. Then we will play some sounds at different listening levels. Some of the sounds will be quieter or louder than others. We will ask you to tell us when you can hear them by pressing a button. We will also play you a series of words in quiet and you will be asked to repeat back the words that you hear. Sometimes we play background noise at the same time and you may find it hard to tell whether there is a sound or not. This shows us how well you can hear in everyday situations.
	We only carry out the tests that are needed to detect a hearing loss. We will inform you of the results, help you to understand your results and how to find out more information. If you would like us to we can write a letter summarising the results if you would like to follow up with your GP or an audiologist. If you choose to follow up with your GP, this will be at your own expense. Should an unexpected hearing impairment be discovered, a full audiological assessment will be offered at the University of Canterbury Speech and Hearing Clinic. Please feel free to ask us lots of questions and to bring someone with you for support.

<u>The matrix sentence test</u>

In this part of the study you will hear short sentences being read in noise. The sentences will have 3 words. After each sentence has been read, you will be asked to repeat what you thought you heard.

This will be repeated with short sentences also being read in quiet, and you repeating back what you thought you heard.

This testing will be repeated but instead of you saying what you think you heard, you will use a touch screen to select the words you heard. Please see below an example.



<u>The QuickSIN™ test</u>

For this part of the study, you will repeat back sentences that you hear in noise. The noise in the background will get louder and the sentences will become increasingly difficult to understand, which is normal.

<u>Cognition test</u>

To test your cognition, you will be asked to complete some simple tasks aimed at assessing your attention, memory, verbal fluency, and ability to draw simple objects.

If your results on the cognition test are outside of what we would normally expect we will discuss these results with you and suggest that you follow this up with your GP if you have any concerns. We can provide you with your results and a summary letter so that you may discuss this further with your GP. It must be noted that scores on this test is not diagnostic by itself but must be interpreted with other clinical information from your GP or other medical specialists.

<u>Data, Confidentiality, and Privacy</u>

- The results of the project will be published as Master theses which will be available via the UC library. The results of the project may also be published as academic journal articles or conference/seminar presentations. The data from this project may also be used in future studies, but in all instances your data will be strictly confidential. Your name, or other identifying information will never be made public.

- To ensure anonymity and confidentiality, your data will be stored in a secure room inside a locked cabinet. In the case of digital data, this will be password protected and stored on password protected devices. Any backups made will be stored on a secure UC server. Your data will be assigned an identification code so that the data can be de-identified. Participant data will only be accessible to members of the research team.

- You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, we will remove information relating to you. However, once the analysis of raw data starts in September 2021, it will become increasingly difficult to remove the influence of your data on the results.

- Any decision not to participate, or to withdraw from the research will not affect your relationship with the University, nor will it affect your access to services provided by the University.

Ethics

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

Consent

- If you agree to participate in the study, you are asked to complete the attached consent form and return it to Natalie Kerr (Master of Audiology Student) or Cynthia McGill (Master of Audiology Student) in person, by post, or by email.

Email: Natalie Kerr natalie.kerr@pg.canterbury.ac.nz

Post: School of Psychology, Speech and Hearing | Te Kura Mahi ā-Hirikapo
College of Science, University of Canterbury
Private Bag 4800, Christchurch 8140, Aotearoa New Zealand

Right to withdraw

Taking part is your choice, and you can withdraw at any stage without giving a reason.

Appendix C

Matrix of testing conditions and order

P	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Retest 1	Retest 2	Retest 3	Retest 4
1	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise closed right	quiet open left	quiet closed right
2	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise closed left	quiet open right	quiet closed left
3	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet closed left	noise closed right	noise open left
4	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise open right	quiet closed left	quiet open right
5	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet open right	noise closed left	noise open right
6	noise open right	noise open left	noise closed right	noise closed left	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise open left	quiet closed right	quiet open left
7	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet closed left	noise open right	noise closed left
8	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet closed right	noise open left	noise closed right
9	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise closed left	quiet open right	quiet closed left
10	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise open right	quiet closed left	quiet open right
11	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise closed right	quiet open left	quiet closed right
12	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise open left	quiet closed right	quiet open left
13	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet open left	noise closed right	noise closed left
14	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet closed right	noise open left	noise closed right
15	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet open right	noise closed left	noise open right
16	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise open left	noise closed right	noise closed left	quiet Open right	quiet closed left	noise open right	noise closed left

P	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Retest 1	Retest 2	Retest 3	Retest 4
17	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise open right	quiet closed left	quiet open right
18	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise open left	quiet closed right	quiet open left
19	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise closed left	quiet open right	quiet closed left
20	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet closed right	noise open left	noise closed right
21	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise closed right	quiet open left	quiet closed right
22	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet closed left	noise open right	noise closed left
23	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	noise open right	noise open right	quiet closed right	quiet open left	noise closed right	noise open left
24	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet open right	noise closed left	noise open right
25	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise open left	quiet closed right	quiet open left
26	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet closed right	noise open left	noise closed right
27	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise open right	quiet closed left	quiet open right
28	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet closed left	noise open right	noise closed left
29	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise closed left	quiet open right	quiet closed left
30	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet open right	noise closed left	noise open right
31	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise closed right	quiet open left	quiet closed right
32	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet open left	noise closed right	noise open left

P	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Retest 1	Retest 2	Retest 3	Retest 4
33	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet closed right	noise open left	noise closed right
34	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet closed left	noise open right	noise closed left
35	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	quiet closed right	quiet open left
36	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet open right	noise closed left	noise open right
37	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise open right	quiet closed left	quiet open right
38	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet open left	noise closed right	noise open left
39	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise closed left	quiet open right	quiet closed left
40	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise closed right	quiet open left	quiet closed right
41	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet closed left	noise open right	noise closed left
42	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet open right	noise closed left	noise open right
43	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet closed right	noise open left	noise closed right
44	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet open left	noise closed right	noise open left
45	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise open left	quiet closed right	quiet closed left
46	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise closed right	quiet open left	quiet closed right
47	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise open right	quiet closed left	quiet open right
48	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise closed left	quiet open right	quiet closed left

P	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Retest 1	Retest 2	Retest 3	Retest 4
49	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet open right	noise closed left	noise open right
50	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet open left	noise closed right	noise open left
51	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet closed left	noise open right	noise closed left
52	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise closed right	quiet open left	quiet closed right
53	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet closed right	noise open left	noise closed right
54	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise closed left	quiet open right	quiet closed left
55	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise open left	quiet closed right	quiet open left
56	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise open right	quiet closed left	quiet open right
57	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet open left	noise closed right	noise open left
58	noise closed left	noise closed right	noise open left	noise open right	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise closed right	quiet open left	quiet closed right
59	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet open right	noise closed left	noise open right
60	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise closed left	quiet open right	quiet closed left
61	quiet open right	quiet open left	quiet closed right	quiet closed left	noise open right	noise open left	noise closed right	noise closed left	quiet open right	quiet closed left	noise open right	noise closed left
62	noise closed left	noise closed right	noise open left	noise open right	quiet closed left	quiet closed right	quiet open left	quiet open right	noise closed left	noise open right	quiet closed left	quiet open right
63	quiet open left	quiet open right	quiet closed left	quiet closed right	noise open left	noise open right	noise closed left	noise closed right	quiet open left	quiet closed right	noise open left	noise closed right
64	noise closed right	noise closed left	noise open right	noise open left	quiet closed right	quiet closed left	quiet open right	quiet open left	noise closed right	noise open left	quiet closed right	quiet open left

Appendix D

Certificate of completion of Mini-ACE administration course

CERTIFICATE of ACHIEVEMENT

This is to certify that

Natalie kerr

has completed the course

Mini-ACE Cognitive Examination

July 30, 2021

Credit Hours: 1.0

The completion of this course awards
1.0 hours PD/CME Points