EFFECTS OF HIGH FREQUENCY HEARING LOSS ON THE UNIVERSITY OF CANTERBURY ADAPTIVE SPEECH TEST – FILTERED WORDS (UCAST-FW)

A thesis submitted in partial fulfilment of the

requirements for the Degree

of Master of Audiology

in the University of Canterbury

by Ali Abu-Hijleh

University of Canterbury

2011

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Terms

AFC	Alternative forced choice
APD	Auditory Processing Disorder
ASHA	American-Speech-Language-Hearing Association
CANS	Central auditory nervous system
CAPD	Central Auditory Processing Disorder
CHABA	Committee on Hearing and Bioacoustics and Biomechanics
CID W-22	Central Institute for the Deaf W-22 lists
CRWT	Compressed and Reverberated Words Test
CVC	Consonant-vowel-consonant
DDT	Dichotic Digit Test
DSI	Dichotic Sentence Identification
HFHL	High frequency hearing loss
HFPTA	High frequency pure tone average
LE	Left ear
LFPTA	Low frequency pure tone average
LPF	Low-pass filter
MoCA	Montreal Cognitive Assessment
NH	Normal hearing
NU-CHIPS	Northwestern University Children’s Perception of Speech Test
PB	Phonetically balanced
PH	Predictability-high
PL	Predictability-low
PPS	Pitch Pattern Sequences
PR	Rractice run
PTA	Pure tone average

QuickSIN	Quick Speech-in-Noise Test
RE	Right ear
SCAN-A	Screening Test for Auditory Processing Disorder in Adults
SCAN-C	Screening Test for Auditory Processing Disorder in Children
SPIN	Speech Perception in Noise test
SSI	Synthetic Sentence Identification
SSI-ICM	Synthetic Sentence Identification - Ipsilateral Competing Message
UCAST-FW	University of Canterbury Adaptive Speech Test – Filtered Words

Units

dB A	A-weighted sound pressure level in decibels
dB HL	Hearing level in decibels
dB SL	Sensation Level in decibels
dB SPL	Sound pressure level in decibels
Hz	Hertz
kHz	Kilohertz
ms	Milliseconds
s	Seconds

Acknowledgements

The Prophet Muhammad *(peace be upon him)* said: ***"God, His angels and all those in Heavens and on Earth, even ants in their hills and fish in the water, call down blessings on those who instruct others in beneficial knowledge."*** *– (Al-Tirmidhi; Hadith 422*)

I would like to express my sincere thankfulness, appreciation and upmost gratitude to my supervisors Dr Greg O’Beirne, Dr Natalie Rickard and Dr Megan McAuliffe for their knowledge, guidance, patience and continuous encouragement throughout this study and for all their helpful suggestions that resulted in a much improved thesis, particularly during the hard times of the Christchurch Earthquakes.

I would also like to say a big thanks to Professor David Hawkins for his advice and help in developing the test procedures used in this study and to Dr Emily Lin for her assistance and advice with the statistical analyses of the results of this study.

Thanks are also due to Resound for their generous support in funding some of the equipment used in this study.

Additionally, I would also like to thank all the participants for their involvement in this study.

Lastly I would like to thank my family and flatmates for their endless support and great patience in putting up with me while writing this thesis.

1 Abstract

Objective: The primary purpose of this study was to determine the influence of high frequency peripheral hearing loss on test performance on the University of Canterbury Adaptive Speech Test – Filtered Words (UCAST-FW). We also aimed to investigate (1) if there is an ear advantage in performing the UCAST-FW; (2) whether there is any correlation between the UCAST-FW score and age; (3) the effectiveness of a binaural practice run in reducing the learning effect; and (4) the average time required for older adults to complete the UCAST-FW.

Method: A total of 18 participants with normal hearing (≤ 25 dB Hearing Level (HL) at octave intervals of 250 through 4000 Hz in both ears) and 19 participants with varying degrees of high frequency sensorineural hearing loss (>25 dB HL at frequencies above 1000 Hz) were included in this study. All participants were native New Zealand English speakers, aged between 55-71 years, with normal low frequency hearing (≤25 dB at 250, 500 and 1000 Hz), had speech scores consistent with their audiogram, normal cognition and judged by the examiner to be capable of completing test protocols in terms of sufficient eyesight, alertness and motor control. Participants underwent a full diagnostic hearing test, the Montreal Cognitive Assessment, the Dichotic Digits Test, the Random Gap Detection Test and the UCAST-FW.

Results: Findings indicated that the presence of a high frequency peripheral hearing loss had no significant influence on the UCAST-FW score. Findings also showed no significant ear advantage, or any trend between the participant's UCAST-FW score and their age. A binaural practice run comprised of 5 initial and 15 working reversals was effective in reducing any learning effect. The UCAST-FW took an average of 15 minutes to complete, and the results showed no correlation between the test completion time and the participant's age.

Conclusion: Findings suggested that the listener's high frequency peripheral hearing sensitivity had no significant influence on their UCAST-FW score and thus the UCAST-FW can potentially be an effective test for assessing Auditory Processing Disorder (APD) in older adults and the elderly regardless of their high frequency peripheral hearing sensitivity. The development of test material in New Zealand English, as well as the investigation of the validity of the UCAST-FW in assessing APD in older adults and the influence of cognitive functioning on test performance is necessary before the UCAST-FW can be implemented in New Zealand clinical Audiology settings.

2 Introduction

The percentage of individuals aged 65 years and older is predicted to increase markedly over the next few decades (Etzioni, Liu, Maggard, & Ko, 2003). The prevalence of hearing loss in older adults and the elderly population is high and tends to increase with increasing age (Gates, Cooper, Kannel, & Miller, 1990). Approximately 40% of adults aged 60 years and older have a hearing impairment sufficient to result in speech understanding difficulties (Gates et al., 1990). Given the increasing elderly population and the increasing prevalence of hearing loss with age, an expanding proportion of the population will experience hearing loss (Pichora-Fuller & Souza, 2003).

Hearing loss in older adults may be caused by exposure to noise, disease or infection, ototoxic drugs, tumours, trauma, and generalised effects of the ageing process (ASHA, 2005; Kiessling et al., 2003). Hearing loss associated with ageing is known as presbycusis. Presbycusis is typically characterised by an acquired, bilateral, sensorineural hearing loss of gradual onset that begins at the high end of the 20 Hz to 20 kHz range of human hearing (Frisina & Frisina, 1997; ASHA, 2005). This hearing loss is usually progressive in nature, with the earliest changes confined to frequencies above 1000 Hz (CHABA, 1988). While the process begins in early adulthood, it is not until 55 years and older that declines in hearing sensitivity usually occur over the important speech frequency range, that is, from 250 through to 4000 Hz (Strickland & Viemeister, 1994), are seen (Frisina & Frisina, 1997; ASHA, 2005). The magnitude of presbycusis varies widely, but typically increases with age, resulting in greater difficulties with speech understanding, especially in acoustically challenging situations such as noisy and reverberant environments (Divenyi, Stark, & Haupt, 2005; Gates & Rees, 1997).

Hearing loss has been shown to negatively affect the listener’s physical, cognitive, behavioural and social functions, as well as general quality of life (Arlinger, 2003).

Longstanding uncorrected hearing loss in adults often leads to isolation from social activities, depression and loss of self-esteem (Arlinger, 2003; Gordon-Salant, 2005). In addition, a significant correlation between uncorrected hearing loss and reduced cognitive function has been shown (Arlinger, 2003). Furthermore, hearing loss places increased demands on family, friends, and co-workers of those affected (Arlinger, 2003).

2.1 Factors underlying presbycusis

In 1988, the National Research Council's Committee on Hearing, Bioacoustics and Biomechanics Working Group on Speech Understanding and Ageing produced a comprehensive review of the factors underlying speech understanding difficulties associated with ageing (CHABA, 1988). Three main components were reported to contribute to presbycusis: (1) peripheral changes in auditory function; (2) changes in central auditory processes; and (3) declines in cognitive functions (CHABA, 1988).

The peripheral auditory system, consisting of the external, middle and inner ear, and the peripheral portion of the eighth cranial nerve (CHABA, 1988), is involved in the detection of acoustic stimuli and the encoding of these signals into nerve impulses that are transmitted to the central auditory nervous system (CANS) (Willott, Hnath Chisolm, & Lister, 2001). In the CANS, a number of central auditory processes analyse and modify the code from these trains of nerve impulses into consciously perceived sounds (Willott et al., 2001; CHABA, 1988). This information is further processed by cognitive functions that are not strictly limited to the auditory system, but act to enhance the perception of the acoustic signal, make sense of the incoming message and store information in memory for future use (Willott et al., 2001; CHABA, 1988). In this complex process, the listener depends on all three of these factors to understand speech. Thus a decline in any of these factors, in isolation or in combination, can result in corresponding age related declines in speech recognition and understanding (CHABA, 1988). One of the major difficulties in the assessment of auditory processing changes in older adults is the influence of peripheral hearing loss and cognitive declines, typically observed concurrently, on test results of currently available Auditory Processing Disorder (APD) measures. This study will focus on establishing the effectiveness of using an adaptive low-pass filtered speech test in the assessment of APD, independent of the high frequency peripheral hearing decline typically seen in this population. A vast number of studies have examined the degree of contribution of each of these three factors to the speech understanding difficulties experienced by older adults and the elderly with presbycusis, some of which are outlined below.

2.2 Contribution of peripheral hearing loss to presbycusis

Declines in peripheral hearing sensitivity in older adults and the elderly are generally thought to be the result of age related structural degenerations in the cochlea (Gates et al., 1990; Johnsson & Hawkins, 1972; Jorgensen, 1961). The degree of peripheral hearing decline can be further increased by other factors such as noise induced damage from recreational and occupational exposure to intense sound and from the biological effects of diseases and ototoxic drugs (Gates et al., 1990). These degenerations in the auditory periphery result in the attenuation and distortion of the acoustic signal (Jerger, Jerger, Oliver & Pirozzolo, 1989). The contribution of declines in the peripheral auditory system to speech understanding difficulties has been extensively studied. Humes and Roberts (1990) examined the contribution of peripheral hearing loss to the speech understanding difficulties experienced by a group of hearing impaired elderly. They compared the monaural and binaural speech identification performance between young normal hearing adults (n=13; aged between 19 - 34 years), young normal hearing adults with simulated hearing loss via noise masking (n=10, aged between 19 - 34 years) and a group of hearing impaired elderly (n=13;

aged between 65 - 75 years) on a wide range of listening conditions. Results showed that the hearing impaired elderly group performed worse than the group of young normal hearing adults on all speech identification tasks. However, virtually identical scores were achieved by the hearing impaired elderly and normal hearing adults with a simulated hearing loss. Furthermore, results of the elderly group showed strong negative correlations (r = -0.77 to -0.94) between the pure tone average (at 1000, 2000 and 4000 Hz) and speech identification scores in all listening conditions. From these results, they concluded that the degree of peripheral hearing loss accounted for most of the individual variations in speech recognition performance of the hearing impaired elderly.

Similar findings were reported by Humes, Watson, Christensen, Cokely, Halling and Lee (1994) who examined the speech recognition performance of 50 participants (aged between 63 - 83 years, M = 72.3 years) on a wide range of speech materials and listening conditions. They also assessed the participants' auditory processing abilities and cognitive function. They reported that differences in peripheral hearing sensitivity were the primary determinant of differences in speech recognition performance and accounted for 70-75% of the variance observed on 20 different speech recognition measures. They further reported that differences on measures of auditory processing and cognitive function accounted for little or no additional variance. A number of other studies have also suggested that peripheral loss of hearing sensitivity accounts for much of the speech understanding difficulties in presbycusis (Jerger, Jerger, & Pirozzolo, 1991; Van Rooij & Plomp, 1992; Lee and Humes, 1993; Humes, 1996).

2.3 Contribution of cognitive factors to presbycusis

The contribution of age related cognitive declines have also been well described in the literature. The prevalence of mild cognitive impairment in older adults aged 65 years and older ranges from three to 18 percent (Portet et al., 2006). The perceptual analysis of the acoustic signal is influenced by higher level, non-modality specific cognitive factors that are not necessarily unique to the processing of auditory information such as attention, learning, motivation, memory and decision processes (ASHA, 1996). Declines in cognitive skills occur with age and hence, the prevalence of cognitive impairment also increases with increasing age (Sweetow, 2005; Lopez et al., 2003). It has been shown that processing speed and working memory decline with age, both of which are important for the comprehension of rapid and distorted speech (Kiessling et al., 2003). In addition, the response task used may also place additional demands on cognitive processing (Humes, 2009). As a result, cognitive deficits may also influence performance on behavioural tests of auditory processing when speech is employed as a stimulus.

2.4 Central auditory processing

Central auditory processing refers to the processing and manipulation of the acoustic information transduced by the peripheral auditory system, which is essential for the interpretation and understanding of that acoustic message (ASHA, 1996; Moore, 2006; Musiek, Geurkink, & Kietel, 1982). Auditory processing is performed by the CANS, which is a complex system with multiple components and levels. Anatomically, the CANS consists of nuclei and pathways in the brainstem, subcortex, primary and association areas of the cortex and corpus callosum (ASHA, 1996).

The terms “Central Auditory Processing Disorder (CAPD)” and “Auditory Processing Disorder (APD)” have been used interchangeably in the literature. In 2000, Jerger and Musiek stated that “central” and “processing” are redundant words and recommended the use of the term “Auditory Processing Disorder”. The American Speech-Language-Hearing Association (1996) defined APD as a heterogeneous disorder, incorporating impairments of various aspects of auditory processing in the CANS as demonstrated by an observed deficiency in one or more of the following behaviours: sound localization and lateralization; auditory discrimination; auditory pattern recognition; temporal aspects of audition, including temporal resolution, temporal masking, temporal integration and temporal ordering; auditory performance decrements with competing acoustic signals; auditory performance decrements with degraded acoustic signals.

More recent reports have defined APD as an auditory-specific perceptual deficit in the processing of auditory stimuli that can occur in spite of normal peripheral hearing sensitivity, and is not due to higher order language, cognitive or related factors (British Society of Audiology, 2007; Moore, 2006). Adults with APD often report difficulties in understanding speech in acoustically challenging environments, particularly in noisy and reverberant settings, as well as difficulties understanding speakers with foreign accents or rapid speech rates (Wingfield & Tun, 2001; Martin & Jerger, 2005). These difficulties are more pronounced in listeners with APD and an accompanying peripheral hearing loss (Stach, Loiselle, & Jerger, 1991).

The exact cause of APD in most adult listeners is not well understood.However, histopathological and morphological studies have documented age related structural degenerations in the auditory nerve (Krmpotic-Nemanic, 1971; Schuknecht, 1964) and the central auditory pathways at both the brainstem and temporal lobe levels (Hinchcliffe, 1962; Kirikae, Sato, & Shitara, 1964; Jerger et al., 1989). These age related structural changes in the CANS are thought to lead to APD in adults (Jerger et al., 1989; Hinchcliffe, 1962; Jerger et al., 1991). In some cases, APD can result from a clear central nervous system pathology arising from a cerebral vascular accident, traumatic brain injury, tumour, epilepsy, Alzheimer’s disease, or multiple sclerosis (ASHA, 1996).

2.5 Contribution of auditory processing disorder to presbycusis

Although numerous studies have suggested that declines in speech recognition performance seen in older adults may be explained by declines in peripheral hearing sensitivity, some investigators have suggested that auditory processing declines may at least partly contribute to speech understanding difficulties. Indeed, significant speech recognition difficulties are seen in some older adults with normal peripheral hearing sensitivity. Frisina & Frisina (1997) investigated the contribution of peripheral hearing loss and APD to speech recognition difficulties in a group of 50 young and elderly adults. Participants included 10 young adults with normal peripheral hearing sensitivity (Young-N) aged between 18 and 39 years and 10 elderly adults with normal peripheral hearing sensitivity (Old-N) aged 60 to 81 years. The remaining 30 participants were elderly with varying degrees of mild high frequency hearing loss and were grouped into three groups of 10 subjects each according to their pure tone thresholds at 4 kHz. Speech reception performance in quiet and in noise was measured utilizing an adaptive paradigm and three different types of speech materials which included, spondee words in isolation, target words in sentences that provided supportive context for identification of the target word, and target words in sentences that did not provide supportive context for the identification of the target word. Comparison between scores of the Young-N and Old-N participants matched on speech reception performance in quiet showed that Young-N participants performed better than Old-N participants on speech in noise tasks. Furthermore, findings showed no difference in mean scores between Young-N and Old-N subjects on their ability to benefit from supportive context in sentence items, suggesting that cognitive functions did not account for the poorer performance in the Old-N participants. These results showed that the better speech understanding performance in noise by Young-N subjects could not be accounted for by the degree of peripheral hearing sensitivity or decline in cognitive functions and strongly suggested that central auditory processing factors accounted for the observed differences in performance. It was also demonstrated that both Young-N and Old-N groups performed better than each of the hearing loss groups on all speech materials. Overall, the results suggested that declines in speech perception can occur independently of declines in peripheral hearing and cognitive functions, and that in patients with a peripheral hearing loss speech understanding difficulties in quiet and especially in noisy environments can result from a combination of peripheral hearing loss and central auditory factors.

Similar findings were also observed by Rodriguez, DiSarno & Hardiman (1990), who assessed central auditory processing and linguistic functions in 25 essentially normal hearing (within 25 dB HL at 0.25, 0.5 and 1.0 kHz, and within 35 dB HL at 2.0 and 4.0 kHz), cognitively intact elderly adults aged between 60 and 85 years on several measures of central auditory processing function. Results showed that 15 (60%) participants exhibited an SSI rollover greater than 20%. They concluded that an APD can occur without a concomitant decline in peripheral hearing sensitivity, cognitive function, or linguistic competence. Similar findings have also been reported by other investigators (Jerger et al., 1989). In general, these studies suggested that age related central auditory processing declines can have a negative influence on speech recognition performance and can occur either independently or in combination with declines in peripheral hearing loss and cognitive functions.

2.6 Measures of auditory processing disorder

Due to the complexity and heterogeneous nature of APD, no one single test has been developed which forms a 'gold standard' for assessment (Medwetsky, 2002; Musiek, Bellis, & Chermak, 2005). Currently, it is recommended that a comprehensive test battery approach be used in the assessment of APD (ASHA, 1996). An APD test battery usually comprises the following categories of behavioural auditory measures in order to assess the various central auditory processing behaviours described above (ASHA, 1996):

- *Temporal processing tests:* to assess the ability of the auditory system to process time related cues in an acoustic signal.
- *Dichotic speech tests:* to assess the ability of the auditory system to binaurally integrate and/or separate simultaneously presented speech stimuli.
- *Binaural interaction:* to assess binaural processes that underlies the timing, lateralisation, and localisation of acoustic stimuli.
- *Monaural low-redundancy speech tests:* to assess the ability of the auditory system to process speech with reduced intelligibility.

Though a wide range of tests have been developed in each of these categories, one of the greatest limitations of using most of the currently available tests for the assessment of APD in older adults and the elderly is the influence of peripheral hearing loss on test performance (CHABA, 1988). This limitation is discussed in section 2.8.

2.7 Prevalence of auditory processing disorder

Reported estimates of the prevalence of APD among older adults and the elderly population vary widely. It has been estimated that approximately 20% of the nonclinical population exhibit APD; however, estimates as high as 95% have been reported in some clinical studies (Stach, Spretnjak, & Jerger, 1990; Cooper & Gates, 1991; Rodriguez et al., 1990; Golding, Taylor, Cupples, & Mitchell, 2006). Stach et al. (1990) retrospectively analysed the audiometric test results of 700 patients and assessed a further 200 nonclinical volunteers (all aged 50 years and older) to determine the prevalence of APD in these two populations. APD was defined on the basis of patterns of test results from the Synthetic Sentence Identification (SSI) test and phonetically balanced (PB) word test – its presence was established when the SSI rollover index exceeded 20%, the PB-SSI difference exceeded 20%, or the absolute SSI score was lower than normal based on the degree of hearing loss. Results showed that the prevalence of APD increased substantially as a function of increasing age in both the clinical and nonclinical groups. In the clinical group, 17% of the patients in the 50 to 54 year age group had some degree of APD, 58% of patients aged between 65 and 69 had APD, while 95% of those 80 years or older showed evidence of APD. The nonclinical sample showed a lower prevalence of APD in each of the age groups, ranging from 0% in the youngest group (aged 50 to 54 years) to 72% in the oldest group (aged 80 years and over). They further showed no significant differences in the prevalence of APD between males and females as a function of age. In addition, Stach et al. (1990) carried out a sub-study in which the degree of peripheral hearing loss was controlled, and demonstrated that a systematic increase of APD with age was still observed.

Cooper and Gates (1991) tested a total of 1018 members of the Framingham Heart Study cohort aged between 64 and 93 years to determine the prevalence of APD in the general elderly population. The presence of APD was established when the Central Institute for the Deaf W-22 lists (CID W-22) in quiet performance intensity function rollover index exceeded 20%, the difference between the SSI test with Ipsilateral Competing Message (SSI-ICM) and CID W-22 scores was greater than 20%, or an abnormal score on the Staggered Spondaic Word test was obtained. Results showed that APD was established in 22.6% of the participants tested.

The wide variations in prevalence reported in the literature are at least partly the result of differences in the measurements and criteria used to determine the presence of APD. Thus as long as there is a lack of a “gold standard”, prevalence estimates will continue to vary. Furthermore, many prevalence studies failed to control for peripheral hearing loss and cognitive declines that can adversely affect performance on speech-based auditory processing tests (CHABA, 1988). However, the available evidence indicates that APD affects a significant proportion of individuals aged 60 years and over and its prevalence increases with increasing age. Gates and Rees (1997) showed that in people aged 70 years or older, central auditory processing declines were greater than peripheral hearing declines, and that APD can be the most significant component of presbycusis in people over the age of 70 years.

Due to the high prevalence of APD in the elderly population, Gates and Rees (1997) recommended routine clinical assessment of central auditory processing for senior patients aged 70 years and over. Others have recommended that auditory processing assessment should be administered for adult patients with hearing difficulties that are greater than would be expected on the basis of their audiogram alone (Bamiou, Liasis, Boyd, Cohen, & Raglan, 2000; Baran, 2002; Cooper & Gates, 1991).

2.8 Effect of peripheral hearing loss on auditory processing disorder measures

Only a few of the currently available auditory processing tests have supporting evidence for their use in the assessment of patients with a peripheral hearing loss. Some authors have reported that mild peripheral hearing loss has minimal effect on the Dichotic Digit Test (DDT) (Musiek, 1983; Speaks, Niccum, & Van Tasell, 1985). Results by Fifer, Jerger and Berlin (1983) showed that the Dichotic Sentence Identification (DSI) test can be used in patients with a pure tone average (at 500, 1000 and 2000 Hz) of up to 48 dB HL with minimal impact on performance. Furthermore, some authors have suggested that non-speech measures such as the Random Gap Detection Test are less likely to be affected by peripheral hearing loss (Strouse, Hall, & Burger, 1995).

However, there is evidence that peripheral hearing loss does negatively influence performance on many of the currently available tests used for the assessment of APD in older adults, including the DDT, DSI and certain non-speech APD measures. Miltenberger, Dawson and Raica (1978) investigated the effect of peripheral hearing loss on APD tests, specifically a dichotic sentence task, a monosyllabic filtered word task, a spondaic word binaural fusion task, and a rapidly alternating speech task. They examined a total of 70 neurologically normal participants (aged between 13 to 65 years) with varying degrees of sensorineural hearing loss. The filtered word task used in the study consisted of monosyllabic words passed through a low-pass filter with a fixed cut-off frequency set at 500 Hz and a rejection rate of 18 dB per octave, presented at 50 dB above the participant's pure tone average. Results revealed that all APD measures administered in this study were affected by certain degrees and configurations of sensorineural hearing loss, with the monosyllabic filtered word task being the most significantly affected. A total of 54 (77%) participants failed one or more of the APD tests, of which 43 participants performed below normal in one or both ears on the monosyllabic filtered word task. Test performance appeared to be particularly affected by the degree of hearing loss at 2000 Hz. The authors recommended that APD test results should be interpreted with caution and in relation to the person's audiogram.

A more recent study by Cox, McCoy, Tun and Wingfield (2008) also investigated the effects of varying degrees of peripheral hearing loss on APD tests used for the assessment of older adults, while controlling for age and cognitive abilities. They tested a total of 45 participants (aged between 66 to 85 years; M = 74.4 years) who were divided into three subgroups of 15 participants, based on hearing acuity; (1) normal hearing from 500 through to 4000 Hz, (2) high frequency sloping hearing loss, and (3) hearing loss in both the low and high frequencies. They compared performance on six monotic APD tests including a low-pass filtered speech test with a fixed cut-off frequency set at 750 Hz (Auditec), the Pitch

Pattern Sequences (PPS) adult test, the QuickSIN Speech-in-Noise Test, the SSI-ICM test, a time-compressed sentence test, and the NU-6 Time-Compressed Speech test. Analysis showed that the PPS and QuickSIN tests were not significantly influenced by peripheral hearing loss, but the SSI-ICM, low-pass filtered speech test, and time-compressed tests were significantly influenced by peripheral hearing loss. The mean low-pass filtered speech score was 69.1% (SD 9.4), 56.3% (19.5) and 54.1% (18.4) for the normal hearing, high frequency sloping hearing loss and low- and high frequency hearing loss groups respectively. The authors suggested that a mild to moderate low- and high frequency peripheral hearing loss may significantly influence APD test results. They further suggested that a mild high frequency sloping hearing loss, typical of early presbycusis, may not have a significant influence on APD test outcomes. They concluded that peripheral hearing sensitivity can significantly influence certain APD test outcomes and suggested that peripheral hearing sensitivity over the frequency range of 500 to 2000 Hz as a key predictor.

These results are further supported by the findings of Jerger et al. (1991) that looked at the influence of peripheral sensorineural hearing loss, age and cognitive status on speech recognition measures that are commonly used in APD test batteries for the assessment of older adults. The study included a total of 200 elderly subjects aged between 50 and 91 years (M = 69.7 years) with a mild to moderate sloping peripheral hearing loss. Five speech recognition measures were used, including the phonemically balanced (PB) word test, the SSI test, the predictability-low (PL) and predictability-high (PH) sentences from the Speech Perception in Noise (SPIN) test, and the DSI test. Findings illustrated significant negative correlations between average high frequency hearing loss and each of the five tests administered. Specifically, for the PB-word, SPIN-PL, SPIN-PH, SSI and DSI scores, Pearson correlation coefficients with hearing loss were -0.68, -0.73, -0.70, -0.48 and -0.44 respectively. Age was identified as a second significant predictor variable of the SSI scores, and the Digit Symbol score from the Wechsler Adult Intelligence Scale was a significant predictor variable for the DSI score, although both age and the Digit Symbol score accounted for far less variance than did peripheral hearing loss. These results showed that performance on all five speech recognition measures, which are commonly part of APD test batteries, are strongly predicted by the degree of hearing loss, while age and cognitive status accounted for little of the variance seen on test performance.

Neijenhuis, Tschur and Snik (2004) looked at the effect of mild hearing loss on APD test outcomes. They examined a total of 54 participants divided into two groups: an experimental group consisting of 24 subjects with a mild, relatively flat, symmetrical sensorineural hearing loss; and a control group consisting of 30 subjects that had normal peripheral hearing. Six APD tests were administered, including a dichotic-digits test, a frequency and duration pattern test, a sentence-in-noise test, a words-in-noise test, a filtered-speech test and a binaural-fusion test. The latter four tests were administered at two presentation levels, the usual presentation level used clinically, and at a level that was adjusted according to the subject’s speech reception threshold. The filtered speech test used 22 words that were filtered using a low-pass filter with a fixed cut-off frequency of 500 Hz and a high-pass filter with a fixed cut-off frequency of 3000 Hz, both with a slope of 60 dB per octave, presented at 65 dB SPL. Comparison between the two groups showed that the hearing impaired subjects’ scores were significantly lower than the control subjects’ scores in all six tests presented at the normal level. After the adjustment of the presentation level, scores on words-in-noise, filtered-speech, binaural-fusion tests and sentences-in-noise improved significantly in subjects with a mild hearing impairment. However, scores were still deviant with the exception of scores on the sentences-in-noise test which fell within normal limits. These results showed that even a mild sensorineural hearing loss can influence certain APD test results.

Humes (2005) looked at the relationship between APD tests and measures of auditory or cognitive function in 213 elderly participants aged between 66 and 88 years (*M* = 73 years). Four APD tests were used, including a duration discrimination, a tonal temporal order discrimination, a dichotic consonant vowel (CV) identification and a 45% time compressed word recognition task. Three subtests of the Wechsler Adult Intelligence Scale - Revised were used to measure cognitive function. Results showed that for the duration discrimination, tonal temporal order discrimination, and dichotic CV identification tasks, differences in performance were primarily predicted by a measure of cognitive function (IQ) and age. For the 45% time compressed word recognition task, the high frequency (1000, 2000 and 4000 Hz) pure tone average (HFPTA) was the primary predictor variable (r=0.73) and accounted for 54% of the total variance in performance. These results give further evidence of the influence of peripheral hearing loss on test performance, especially for speech recognition performance for time compressed monosyllables, and also suggested that cognition can influence test performance on certain APD tests.

These studies provide clear evidence of the negative influence of the presence of even a mild peripheral hearing loss on test performance on many of the currently available APD measures used for the assessment of older adults and the elderly population, including Low-pass filtered speech tests employing a fixed cut-off filter frequency. As a result the sensitivity, specificity and overall validity of using such tests in the assessment and identification of APD in listeners with an accompanying peripheral hearing loss can be significantly compromised. They suggest that a potential false diagnosis of APD can be made if caution is not taken when interpreting APD test results in listeners with a peripheral hearing loss, and that the assessment of APD can be challenging using the currently available APD measures in listeners with a peripheral hearing loss.

Due to the high prevalence (which increases with age) of peripheral hearing loss and cognitive impairment in older adults and in the elderly population, the independent assessment and identification of a true APD can be very challenging. A newly developed adaptive monaural, low-redundancy, low-pass filtered speech test, known as the University of Canterbury Adaptive Speech Test – Filtered Words (UCAST-FW) is proposed to provide an effective measure of assessing APD in the elderly population, regardless of the listener's degree of high frequency peripheral hearing sensitivity. The following section will focus on monaural low-redundancy speech tests, in particular, low-pass filtered speech tests.

2.9 Monaural low redundancy speech tests

Monaural low redundancy speech tests have been frequently used in the assessment of APD (Humes, 2009). A monaural low redundancy speech test involves the monaural presentation of speech stimuli that have been degraded to reduce the inherent redundancy of the signal. Monaural low redundancy speech tests assess central auditory processes involved in listening in noise and to degraded acoustical signals, which are common complaints of patients presenting with APD (Divenyi et al., 2005). They provide valuable and practical information about functional deficits, such as listening in noise and auditory closure problems, which is useful for planning appropriate intervention (Krishnamurti, 2007). The rationale for using degraded speech stimuli is that speech recognition performance deteriorates only when both the intrinsic neural redundancy of the CANS and the extrinsic redundancy of the speech stimulus have been reduced (Bocca & Calearo, 1963). Extrinsic redundancy refers to the redundancy of acoustic information from multiple and overlapping acoustic cues available in spoken language. On the other hand, intrinsic redundancy reflects the multiple representations of an acoustic signal within the neural pathways in the auditory system. Sensory information travelling within the CANS is processed both in a serial and a parallel manner across multiple nuclei, resulting in a highly efficient and redundant system (Demanez & Demanez, 2003; Krishnamurti, 2007). When the extrinsic redundancy of the speech stimulus is degraded to a point where it sufficiently challenges the central auditory processing system, auditory processing is made more difficult (Humes, 2009). Individuals with a normal auditory system can tolerate large amounts of distortion to speech stimuli before the intelligibility of the speech stimuli is significantly reduced (Lacroix, Harris, & Randolph, 1979). However, this ability is often impaired in individuals with APD, with the resulting difficulty significantly pronounced, and thus can be used as an indicator of APD (Humes, 2009).

Degradation or distortion of a speech stimulus can be achieved in a variety of ways, including the addition of competing stimuli, filtering of the speech stimulus, interruption of the speech stimulus, or time compression of the speech stimulus, among others (Humes, 2009). This study will focus on a category of monaural low redundancy speech tests known as low-pass filtered word tests, in which speech stimuli are distorted by using filtering to modify the frequency content.

2.10 Low-pass filtered speech tests

In low-pass filtered speech tests, the speech stimuli are degraded by using a low-pass filter that alters the frequency content by removing high frequency information of the speech spectrum above a specified filter cut-off frequency. The sounds of speech contain acoustic energy between approximately 100 Hz to just above 8000 Hz (Noordhoek, Houtgast, & Festen, 1999). The removal of high frequency information affects consonant recognition more than vowel recognition, which is more crucial for speech understanding (Bornstein, Wilson, & Cambron, 1994; Rintelmann, 1985). The intelligibility of the speech signal varies and depends on the filter cut-off frequency of the low-pass filter employed and the rejection rate of the filter used. The lower the filter cut-off frequency and the higher the rejection rate, the less frequency information remains and the more difficult the speech stimulus becomes to discriminate.

The use of low-pass filtered speech in auditory testing emerged in the 1950s after publications by Bocca and colleagues (Bocca, Calearo, & Cassinari, 1954; Bocca, Calearo, Cassinari, & Migliavacca, 1955). Bocca et al. (1954) were the first to recognise that peripheral auditory testing and vocal speech tests were insensitive in detecting auditory difficulties reported by patients with temporal lobe lesions. This is due to the high degree of extrinsic redundancy available in speech stimuli used in standard speech tests (Humes, 2009). Bocca and colleagues hypothesised that it was necessary to reduce the extrinsic redundancy of speech stimuli in order to develop a test sensitive to challenge the CANS and identify possible lesions. Bocca et al. (1954) reduced the extrinsic redundancy of speech stimuli by filtering the speech through a low-pass filter with a cut-off frequency that eliminated frequency information above 500 Hz. They reported that adult patients with temporal lobe lesions yielded poorer discrimination scores on low-pass filtered speech for the ear contralateral to the lesioned hemisphere. Subsequent studies have supported the value of using low-pass filtered speech tests in the identification of cortical lesions and for the assessment of APD (Jerger, 1960; Calearo & Antonelli, 1963).

There are at least three test batteries currently commercially available that include a low-pass filtered speech test. The Flowers-Costello Test of Central Auditory Abilities consists of a subtest that uses sentences that have been low-pass filtered with a fixed cut-off frequency of 960 Hz (Flowers, Costello, & Small, 1970). A second test battery, the Willeford central test battery includes the Ivey Filtered Speech Test, which uses open set Michigan Consonant-Vowel-Consonant (CVC) words that are low-pass filtered using a fixed cut-off frequency of 500 Hz, with higher frequencies attenuated at a rejection rate of 18 dB per octave (Willeford, 1977). The SCAN-C and SCAN-A test batteries used to assess auditory processing disorders in children and in adolescents/adults respectively, both also include a filtered words subtest (Keith, 1994; Keith, 2000). The SCAN filtered subtest uses an open set response, with stimuli low-pass filtered with a fixed cut-off frequency of 1000 Hz and a 32 dB per octave rejection rate.

A major limitation of these commercially available low-pass filtered speech tests is that they are carried out using a constant level of low-pass filtering (i.e. a fixed filter cut-off frequency) which makes them prone to ceiling and floor effects (i.e. scores near either 100% or 0%) (Farrer & Keith, 1981). As a result, the efficiency and sensitivity of these tests are significantly compromised (Martin & Clark, 1977; Farrer & Keith, 1981). In other words, if the cut-off frequency is set too low, the test may be too difficult for individuals with normal APD, as well as those with APD. On the other hand, if the cut-off frequency is set too high, then even individuals with APD will achieve high scores and pass the test. Furthermore, the different versions of low-pass filtered speech tests have all employed a different filter cut-off frequency. While some studies have compared the effect of different cut-off frequencies (Farrer & Keith, 1981), little research has investigated the most effective filter cut-off frequency for clearly differentiating between individuals with and without APD. These limitations can be avoided by using an adaptive testing procedure. Contrary to the constant level methods, in which stimuli are presented at a fixed, predetermined presentation parameter (e.g. a fixed filter cut-off frequency), the presentation parameter of a stimulus in adaptive testing procedures is varied depending on the listener's response to the proceeding stimulus (Levitt, 1971). Adaptive testing procedures have a number of advantages over constant level procedures. Firstly, adaptive procedures vary the degree of test difficulty by adapting the presentation parameter of the stimuli to suit the listener's ability, therefore the test can be neither too easy nor too hard for the participant. As a result, ceiling and floor effects are avoided (Mackie & Dermody, 1986). Secondly, because the threshold level is determined by the listener's performance, there is no need to predetermine an optimal fixed presentation level (Mackie & Dermody, 1986). Further advantages of adaptive testing procedures over constant-level methods include improved efficiency, greater flexibility, as well as higher reliability, precision and inter-test consistency (Levitt, 1971; Mackie & Dermody, 1986; Leek 2001; Zera, 2004; Sincock, 2008).

2.11 The University of Canterbury Adaptive Speech Test – Filtered Words (UCAST-FW)

The UCAST is an adaptive speech test platform developed by Dr Greg O'Beirne and written using LabVIEW 8.20 (National Instruments, TX, USA). In this study it was used to conduct an adaptive, monaural, low redundancy, low-pass filtered speech test (UCAST-FW) for the assessment of auditory processing abilities in adults. The UCAST-FW aims to eliminate the effect of any high frequency peripheral hearing loss on test performance by using low-pass filtered speech, resulting in test items with spectral content almost entirely below 1 kHz.

McGaffin (2007) assessed the test-retest reliability of the UCAST-FW. A total of 32 children (aged 8 to 11 years, M = 9.9 years) and 23 adults (aged 18 to 55 years, M = 29.8 years), all with normal auditory processing skills, completed the UCAST-FW to determine the threshold at which they scored 70.7% correct. This was then repeated, with an interval of approximately one week between the two test sessions. Findings showed a strong correlation between thresholds obtained by adult participants during the first and second test sessions for both the right ($r = 0.86$) and left ($r = 0.86$) ear scores, suggesting a high test-retest reliability of the UCAST-FW when administered to adult participants. Findings also showed that the 70.7% thresholds for adults under 35 years were significantly lower ($p=0.0014$) than those for adults over 35 years of age and that adult test performance on the UCAST-FW deteriorated with increasing age. The reduced performance shown by the older adult participants, all of whom had normal hearing below 4 kHz, suggested that the UCAST-FW may be effective in assessing APD in older adult participants.

Sincock (2008) utilised the UCAST software to run different adaptive speech tests to evaluate and compare their clinical application to conventional speech audiometry measures, with respect to administration time, accuracy, efficiency and reliability. Findings demonstrated the superiority of the UCAST adaptive speech tests in terms of increased reliability, inter-test consistency, and efficiency in administration time.

Furthermore, Heidtke (2010) compared the performance of 15 children (aged 7 to 13 years) with APD to the performance of an age-matched control group of 10 normally developing children on the UCAST-FW. All children exhibited normal peripheral hearing sensitivity. Results of the study showed a significant difference between the UCAST-FW low-pass cut-off filter frequency required for the APD and control children to achieve a 62.5% threshold level. These findings were interpreted to indicate that the UCAST-FW was a useful tool for discriminating between children with and without APD.

Therefore, these findings suggested that the UCAST-FW can be a potentially effective tool in assessing APD in adults with a high test-retest reliability, as well as increased efficiency and accuracy than currently available low-pass filtered speech tests . One population group that may demonstrate APD and would benefit from an adaptive test that was not influenced by high frequency peripheral hearing loss is the elderly. As earlier demonstrated in this review, the assessment of APD in the older adult population is commonly compromised by the potential contamination of any concurrent declines in peripheral hearing sensitivity and cognitive functions to test results on currently available APD measures. However, by employing an adaptive paradigm that uses low-pass filtered speech material with spectral content almost entirely below 1 kHz, we aimed to eliminate the influence of any high frequency peripheral hearing loss on test performance. Therefore, in the present study our primary aim was to determine whether high frequency peripheral hearing loss affected the performance of older adults on the UCAST-FW.

3 Statement of the problem

Reduced peripheral auditory function, auditory processing disorders and declines in cognitive function all contribute to presbycusis. A decline in one or a combination of these factors can result in deterioration in speech communication that may have severe negative consequences on the individual's quality of life. It is vital to assess and identify the underlying cause of presbycusis to allow for the provision of appropriate and effective rehabilitation (Humes, 2009; Stach et al., 1991). For example, if an elderly patient presents with speech communication difficulties that are primarily due to APD, then fitting this patient with a conventional hearing aid, which tends to be the current primary treatment of presbycusis, may not provide much benefit (Humes, 2009; Stach et al., 1991). Therefore, appropriate targeted rehabilitation can only be provided if the underlying causes of presbycusis are first identified. Current APD tests are generally influenced by the individual's peripheral hearing sensitivity and may be prone to ceiling and floor effects. The UCAST-FW was designed to use low-pass filtered speech material with spectral content almost entirely below 1 kHz, to eliminate the contamination of the presence of any high frequency peripheral hearing loss on test performance. Furthermore, its adaptive procedure ensures that ceiling and floor effects are avoided. Given that the UCAST-FW was designed to account for high frequency hearing loss, it appears likely that it would provide a more effective and reliable tool for the assessment of APD in the elderly – something which may not be obtained using current tests that do not account for high frequency peripheral hearing loss. However, the relative performance of older adults with a hearing loss on the UCAST-FW is yet to be determined. As a result, the primary aim of the current study was to investigate the influence of peripheral hearing loss on the UCAST-FW test performance of older adult listeners. To do so the following questions were posed:

1. Is there a significant difference in the UCAST-FW score between a group of older adults with normal hearing and a group of older adults with a high frequency hearing loss?
2. Is there any correlation between the UCAST-FW score and the listener's high frequency hearing thresholds at 2, 4 or 8 kHz?

We hypothesised that given that the UCAST-FW uses low-pass filtered speech material with spectral content almost entirely below 1 kHz, there would be no significant difference between the normal hearing group and the high frequency hearing loss group. Furthermore, no correlation would be found between performance on the UCAST-FW and the listener's degree of high frequency peripheral hearing loss.

We also aimed to investigate the following secondary questions:

1. Is there an ear advantage in the performance on the UCAST-FW?
2. Is there any correlation between the UCAST-FW score and age?
3. Is a shorter binaural practice run (5 initial and 15 working reversals) than that used by Heidtke (2010) still effective in reducing the learning effect?
4. Is there any correlation between the time required to complete the UCAST-FW and the listener's age and what is the average time required to complete the UCAST-FW?

4 Methods

4.1 Participants

A total of 37 individuals participated in this study, and an additional 9 had to be rejected. All were volunteers who either responded to advertisements soliciting participation (see Appendix 1), heard of the study via word of mouth, or were identified from the University of Canterbury Speech and Hearing Clinic. Each participant received a $10 petrol voucher for his or her participation. Participants were given an information sheet (Appendix 2) and informed consent was obtained from all participants (Appendix 3). All study protocols and procedures were approved by the University of Canterbury Human Ethics Committee (Appendix 4). The study was conducted at the University of Canterbury Audiology Research Centre.

Participants were included in the study if they were: (1) aged between 55 and 71 years; (2) native New Zealand English speakers; and (3) judged by the examiner to be capable of completing test protocols in terms of sufficient eyesight, alertness and motor control. Furthermore, participants were required to exhibit: (4) hearing sensitivity thresholds equal to, or better than, 25 dB Hearing Level (HL) over the frequency range from 250 Hz to 1000 Hz; (5) no conductive hearing pathology (i.e., normal tympanometry and no air-bone gap greater than 10 dB at 500, 1000, 2000 and 4000 Hz); (6) no significant interaural asymmetry (i.e., interaural air conduction threshold differences not greater than 15 dB at two or more frequencies); (7) speech audiometry scores consistent with pure tone thresholds in both ears; (8) no known fluctuating or rapidly progressing hearing loss; and (9) a score of ≥ 26 on the Montreal Cognitive Assessment, MoCA (Nasreddine et al., 2005).

Of the 9 individuals that were rejected in this study, three failed the MoCA, two exhibited pure tone thresholds greater than 25 dB HL at one or more of the frequencies tested over the frequency range of 250 Hz to 1000 Hz, three demonstrated significant interaural asymmetry and one individual exhibited a significant conductive hearing loss.

The remaining 37 individuals were divided into two groups based on their high frequency pure tone thresholds above 1000 Hz. One group, designated the normal hearing (NH) group, comprised of 18 individuals (7 males, 11 females) with pure tone air conduction thresholds better than or equal to 25 dB HL from 1000 to 4000 Hz. The second group, designated the high frequency hearing loss (HFHL) group, comprised of 19 individuals (12 males, 7 females) who exhibited pure tone air conduction thresholds greater than 25 dB HL at 2000 and/or 4000 Hz.

Table 1 contains details of the demographic, cognitive and peripheral audiometric characteristics of the NH and HFHL participant groups. To determine whether the two participant groups differed on any parameters, Mann-Whitney Rank Sum nonparametric tests were completed on parameters of interest. Nonparametric tests were used as the sample collected failed normality and equal variance tests. A significance level of $p \leq .05$ was employed in all analyses. As can be seen, the two participants groups were equivalent in age. While all participants in the study were found to exhibit normal cognition based on their scores on the MoCA, there was a statistically significant difference in the average score across the two groups. As planned based on the participant selection criteria, no significant differences in either the right or left ear pure tone thresholds at 250, 500 and 1000 Hz were noted between the NH and HFHL groups. A significant difference between groups was noted for the High Frequency Pure Tone Average (HFPTA) (average of thresholds at 2, 4 and 8 kHz); though when the pure tone thresholds at 2, 4 and 8 kHz were analysed separately, a significant difference was found only at 4 and 8 kHz. Figure 1 displays box and whisker plots depicting the average of the peripheral hearing thresholds of the right and left ears of the NH group (Figure 1A) and the HFHL group (Figure 1B).

In general, participants in the HFHL group showed a sloping sensorineural high frequency hearing configuration, consistent with the classic presbycusic peripheral hearing configuration. No air-bone gaps were noted for any of the participants included in the study. The majority of participants had Type A tympanograms bilaterally consistent with normal middle ear pressure and compliance. Five participants in the NH group and 2 participants in the HFHL group showed a Type Ad tympanogram in either one or both ears, consistent with excessive tympanic membrane mobility. In the HFHL group, 1 participant presented with a Type As tympanogram, consistent with reduced middle ear compliance.

Table 1. Summary of demographic, cognitive, and audiometric characteristics, including separate right ear (RE) and left ear (LE) peripheral auditory characteristics of both the Normal Hearing (NH) group and the High Frequency Hearing Loss (HFHL) group. Statistical significance between groups was determined using the Mann-Whitney Rank Sum Test.

Variable	Participant group				Statistical significance *(p; U)*
	NH Group (n = 18)		HFHL Group (n = 19)		
Sex					
Male	7		12		
Female	11		7		
Age (Years)					
Mean	63.0		64.3		
Median	62.9		64.4		p = 0.533;
Range	56.1 - 71.5		56.3 – 70.6		U = 192.0
Standard deviation	5.0		5.1		
Cognitive Screen (MoCA score)					
Mean	27.7		26.7		
Median	28.0		26.0		p = 0.009*;
Range	26 – 30		26 – 30		U = 90.0
Standard deviation	1.4		1.25		
	RE	**LE**	**RE**	**LE**	
2000 Hz Threshold (dBHL)					
Mean	11.9	11.7	17.4	18.2	RE: p = 0.145;
Median	10.0	10.0	15.0	15.0	U = 218.5
Range	0 – 25	0 – 20	5 – 40	0 – 40	LE: p = 0.125;
Standard deviation	6.5	5.9	10.6	12.0	U = 221.0
4000 Hz Threshold (dBHL)					
Mean	15.0	15.6	44.5	46.3	RE: p = <0.001*;
Median	15.0	15.0	40.0	45.0	U = 342.0
Range	5 – 25	0 – 25	30 – 60	35 – 65	LE: p = <0.001*;
Standard deviation	6.6	7.8	11.2	11.4	U = 342.0
8000 Hz Threshold (dBHL)					
Mean	20.0	27.2	52.6	52.9	RE: p = <0.001*;
Median	15.0	27.5	50.0	55.0	U = 312.5
Range	-5 – 50	0 – 65	20 – 80	30 – 80	LE: p = <0.001*;
Standard deviation	17.2	18.7	15.3	13.7	U = 292.0
Low Frequency Pure Tone Average (.25, .5, 1 kHz) (dBHL)					
Mean	11.0	10.9	12.6	10.3	RE: p = 0.209;
Median	10.8	11.7	13.3	10.0	U = 212.5
Range	1.7 – 25	3.3 – 23.3	5 – 18.3	3.3 – 16.7	LE: p = 0.903;
Standard deviation	5.1	5.0	3.9	4.1	U = 166.5
High Frequency Pure Tone Average (2, 4, 8 kHz) (dBHL)					
Mean	15.7	18.2	38.2	39.1	RE: p = <0.001*;
Median	15.8	17.5	38.3	40.0	U = 336.5
Range	3.3 – 26.7	0 – 36.7	23.3 – 56.7	26.7 – 61.7	LE: p = <0.001*;
Standard deviation	7.2	8.2	9.1	8.9	U = 330.0

* $p \leq 0.05$

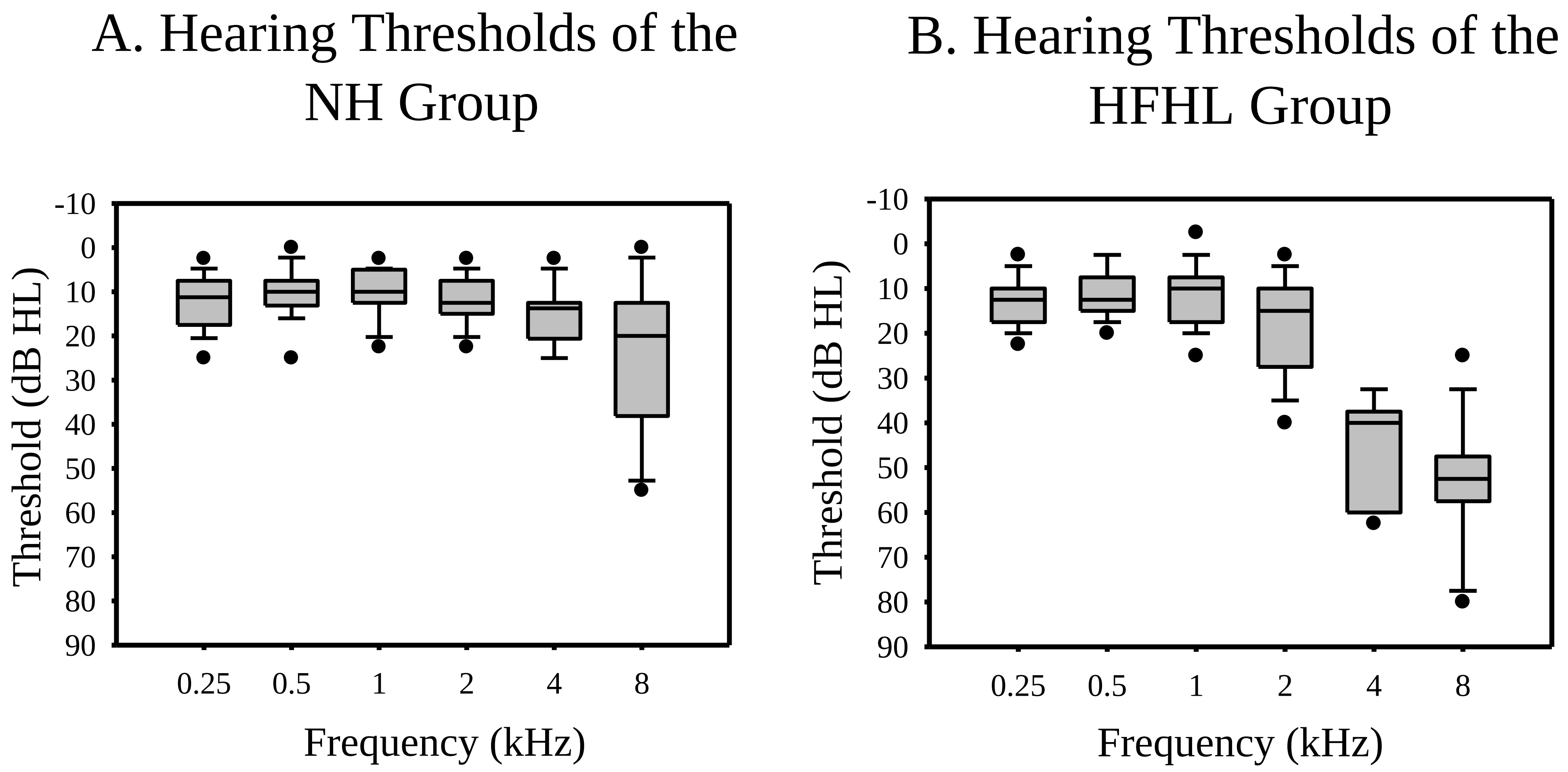

Figure 1. Box and whisker plots showing the distribution of the average of the right and left ear thresholds obtained at octave frequencies between 0.25 and 8 kHz for the Normal Hearing (NH) group (A) and the High Frequency Hearing Loss (HFHL) group (B).

4.2 Procedure

All testing was conducted by the author in a sound treated booth. Participants were required to attend a two hour appointment. Appropriate breaks were provided when necessary to avoid fatigue. Participants first underwent a standard hearing evaluation and a cognitive screening assessment to determine their eligibility for participation. If the participants met the hearing and cognitive criteria for participation, the Dichotic Digits Test (DDT) and the Random Gap Detection Test (RGDT), followed by the experimental component of the study were subsequently completed.

4.2.1 Hearing evaluation

Four standard procedures were conducted as part of the hearing evaluation using the University of Canterbury Speech and Hearing Clinic Audiology Protocols. These included: (1) otoscopy, (2) immittance testing, (3) pure tone audiometry, and (4) conventional speech audiometry.

4.2.1.1 Otoscopic inspection

Otoscopy was performed to examine the participant's external auditory meatus and to check for collapsing ear canals and excessive cerumen.

4.2.1.2 Immittance battery

Immittance testing was carried out using the Madsen OTOflex 100 and OTOdiagnostic Suite (GN Otometrics). Conventional 226 Hz probe tone admittance tympanometry was conducted to assess the middle ear status and help rule out any conductive hearing loss. Tympanometry results were considered normal if the middle ear pressure was ≥100 daPa, and the middle ear compliance was greater than 0.2 millimhos.

4.2.1.3 Pure tone audiometry

Pure tone air conduction thresholds were measured with a GSI 61 Clinical Audiometer, equipped with ER-3A insert earphones or TDH-50P supra-aural headphones, at 250, 500, 1000, 2000, 4000 and 8000 Hz using the Modified Hughson-Westlake ascending method (Carhart & Jerger, 1959). Additional threshold measurements at 750, 1500, 3000 and 6000 Hz were made if thresholds at the adjacent octave test frequencies differed by 20 dB HL or more. Pure tone bone conduction thresholds were measured using a Radioear B-71 bone conductor if an air conduction threshold was greater than 15 dB HL at 500, 1000, 2000 and/or 4000 Hz.

4.2.1.4 Conventional speech audiometry

The National Audiology Centre Millennium CD recording of Boothroyd and Nittrouer's (1988) speech lists were used to assess speech recognition abilities. The recording consisted of twelve meaningful consonant-vowel-consonant (CVC) word lists, each containing ten isophonemic and phonetically balanced words. Speech stimuli played from a standard portable CD player were adjusted to the appropriate presentation level by the GSI-61 Clinical Audiometer and delivered via ER-3A insert earphones or THD-50P supra-aural headphones. Words were recorded by an adult male speaker and each word was preceded by the carrier phrase "Say". Participants were given ample time to repeat the word that they had heard. Participants were also encouraged to guess if they were unsure of any of the stimuli presented. Two to three lists were presented monaurally starting with the better hearing ear. The first presentation aimed to provide a score close to 100%. Participants in the NH group had an initial presentation level at 40 dB HL, while participants in the HFHL group had the initial speech list presented at 30 dB above the average of their 500, 1000 and 2000 Hz pure tone thresholds. The presentation level of the second speech list was set at 10-20 dB below the presentation level of the first list. If the score for the second list was still well above the expected half-peak level, a third speech list was presented at 10-15 dB below the second presentation level. A phonemic scoring system was used to score the participant's responses, and the results of each list of ten words at a single presentation level yielded a percentage correct score.

4.2.2 Cognitive screen

The Montreal Cognitive Assessment (MoCA) (Nasreddine, 2005) is a rapid screening instrument for the detection of mild cognitive dysfunction. It was included to ensure that performance on the UCAST-FW was not influenced by the presence of mild cognitive impairment. The screen assesses different cognitive domains, including attention and concentration, executive functions, memory, language, visuoconstructional skills, conceptual thinking, calculations, and orientation. The MoCA is scored out of 30 points, with a score of ≥ 26 indicating normal cognition. The following test items are included:

i) a short-term memory recall task (5 points), which involved two learning trials of five nouns and delayed recall after approximately 5 minutes;

ii) a clock-drawing task (3 points) and a three-dimensional cube copy task (1 point) used to assess visuospatial abilities;

iii) an alternation task (1 point), a phonemic fluency task (1 point), and a two item verbal abstraction task (2 points) to evaluate multiple aspects of executive functions;

iv) a sustained attention task (1 point), a serial subtraction task (3 points), and recalling digits forward and backward task (1 point each) to assess attention, concentration, and working memory;

v) a three item confrontation naming task with low-familiarity animals (lion, camel, rhinoceros; 3 points) and the repetition of two syntactically complex sentences (2 points) used to assess language;

vi) the final task evaluates the person's orientation to time and place (6 points).

4.2.3 Auditory processing tests

Participants that met the inclusion criteria completed two common behavioural auditory processing tests – the Random Gap Detection Test (RGDT) and the Dichotic Digits Test (DDT) – with test sequence randomised to prevent any order effect. These were included in the test battery to provide some information about the participant's auditory processing abilities. Participant's responses were manually recorded by the examiner on the appropriate scoring sheets. Test items were played using a standard portable CD player connected to the speech input of a GSI 61 clinical audiometer and presented through ER-3A insert earphones or THD-50P supra-aural headphones. The two channels of the audiometer required for the administration of both tests were calibrated separately. In both auditory processing tests, test items were presented at 50 dB above the participant's pure tone average of 250, 500 and 1000 Hz.

4.2.3.1 Random Gap Detection Test (RGDT)

The RGDT, developed by Keith (2000), was used to assess auditory temporal resolution. This test examines the shortest time interval in which a listener is able to distinguish two auditory signals – the gap detection threshold (measured in milliseconds). The RGDT consists of four sets of tonal stimuli at frequencies of 500, 1000, 2000 and 4000 Hz. Each set consists of nine tonal stimuli with a randomly assigned interstimulus interval of either 0, 2, 5, 10, 15, 20, 25, 30 or 40 ms. A practice set, at 1000 Hz and increasing interstimulus intervals from 0 to 40 ms, was used for training. The tones used were 15 ms in duration with a 1.5 ms rise-fall time. The test stimuli were presented binaurally and participants were asked to verbally indicate whether they had heard one or two tones. The gap detection threshold was averaged across the four frequencies to obtain a composite gap detection threshold. This score was used in the final analysis of results.

4.2.3.2 Dichotic Digits Test (DDT)

The DDT (Musiek, 1983) from the National Audiology Centre Millenium CD was used to assess central auditory processing abilities. Dichotic listening tests involve the simultaneous presentation of different acoustic stimuli to each of the two ears. The test items consisted of naturally spoken digits from 1 to 9, excluding the number 7, and were presented dichotically. Five single digit dichotic pairs were presented to ensure familiarity with the task, followed by 20 double digits dichotic pairs for scoring. In the double digits dichotic pairs test, each test item consisted of four digits, two recorded on channel 1 of the CD that was routed to the left ear and two on channel 2 that was routed to the right ear. Participants were asked to listen to each test item consisting of two sequential pairs of dichotically presented digits. Participants were given ample time to recall all four digits and the CD was paused if necessary. The reporting method was free-recall (digit order and ear designation was not monitored) and participants were encouraged to guess if they were unsure of a response. The test consisted of 20 dichotic pairs, giving a total of 40 test items for each ear. The number of correctly recalled digits for each ear was calculated and a percentage correct score for each ear was derived. A total percentage correct score of 90% and above was regarded as normal (Musiek, 1983).

4.2.4 University of Canterbury Adaptive Speech Test – Filtered Words (UCAST-FW)

The UCAST-FW protocols and parameter settings were originally defined by McGaffin (2007) and were later modified by Sincock (2008) and Heidtke (2010). A summary of the UCAST-FW parameters employed in this study are outlined in Table 2. The UCAST-FW protocols and parameter settings used for this study were similar to those used by Heidtke (2010) with some minor software and procedural modifications that included: (1) the use of a 10th order Butterworth filter instead of a 6th order Butterworth filter; (2) the utilisation of written words instead of pictures to display test items; (3) a presentation level of 65 dB Sensation Level (SL) above the participant's pure tone average at 250, 500 and 1000 Hz instead of a 60 dB A; and (4) the use of a total of 20 reversals (5 initial, 15 working reversals) instead of a total of 25 reversals (5 initial, 20 working reversals). An overview of the protocols and parameters settings used in this study is outlined below.

Table 2. Summary of the UCAST-FW parameters and settings.

UCAST-FW Parameter	Setting
Test material	Northwestern University Children's Perception of Speech Test (NU-CHIPS) Book A and B
Acoustic speech stimuli	Australian recording of the NU-CHIPS test "Speech Recognition Materials" CD 1
Adaptive procedure	Weighted up-down procedure
Response format	Four-alternative forced choice written words (4AFC)
LPF cut off frequency threshold level	62.5%
Initial reversals	
Number of reversals	5
Step size	20.83%
Working reversals:	
Number of reversals	15
Step size	8.33%
Termination criteria	20 reversals
Starting LPF Frequency	1000 Hz
Presentation	Binaural practice run, followed by monaural presentations in randomised order.
Filter setting	10^{th} order Butterworth filter
Presentation level	65 dB Sensation Level re PTA at 250, 500 & 1000 Hz.

4.2.4.1 Equipment

A desktop computer (Intel (R) Core (TM) 2 Duo CPU E7500 at 2.93 GHz, 1.98 GB of RAM) was used to run the UCAST-FW. The speech stimuli were presented via Sennheiser HD 215 supra-aural headphones driven by an InSync Buddy USB 6G sound-card connected to the desktop computer. An external ELO ET1715L 17 inch touch screen monitor (Tyco Electronics Corp., USA), was used to visually present the four alternative word choices to the participants as shown in Figure 2, and to receive their responses.

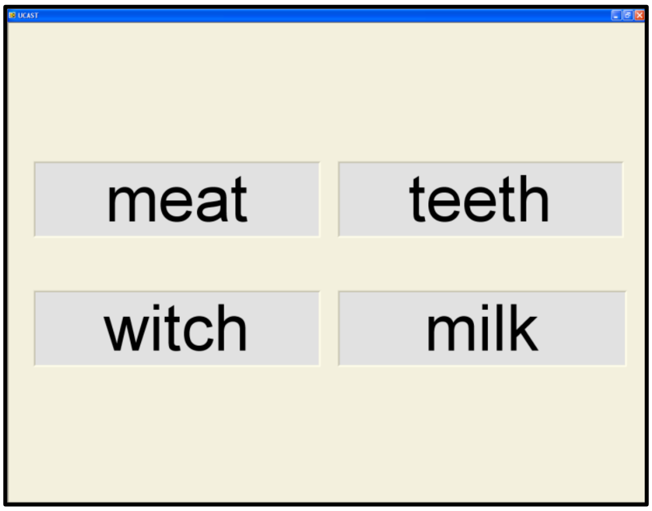

Figure 2. A screenshot of the UCAST-FW touch screen display, showing an example of four alternative test items, one corresponding to the acoustically presented word and the other three acting as foils. The participant selected the word they thought they heard.

4.2.4.2 Test material

The same test materials used in the preceding work by McGaffin (2007), Sincock (2008) and Heidtke (2010) were used in this study. This comprised of the Australian recording of phonetically balanced monosyllabic word lists from the Northwestern University Children's Perception of Speech Test (NU-CHIPS) Book A and B, developed by Elliott & Katz (1979). The Australian recording was used due to the lack of a four-alternative forced choice test material in New Zealand English. Although speech material presented in a non-native accent can influence speech understanding (Gordon-Salant et al., 2010), the Australian recording was used in this study to assess the methodology before going through the complexities of designing and recording a New Zealand English version. The acoustic recordings of the word lists were taken from the “Speech Recognition Materials” CD 1 developed by the National Acoustic Laboratories (Chatswood, NSW, Australia). The NU-CHIPS test, originally designed as a four alternative forced choice picture pointing task, consists of 65 monosyllabic words that are interchanged as test items and foil items. The test contains four sets of 50 trials, each trial has one test item and three other items acting as foils chosen in a randomised order. Although the NU-CHIPS test was designed for testing children aged 2.5 years and over, the current study used written words instead of pictures, to make it more suitable for use with adult participants.

4.2.4.3 Starting Low-Pass Filter (LPF) frequency

McGaffin (2007) suggested that the most efficient starting LPF corner frequency was 1000 Hz. This was based on findings by Carhart and Jerger (1959) and Garcia-Perez (1998) that suggested that the optimal starting point should be a balance between a supra-threshold level that provides the participant with clear examples and conditions the participant to the task; and a level that is not so far from threshold that it will reduce the efficiency of the test. McGaffin (2007) reported that at this 1000 Hz LPF starting point, the initial test item was accurately identified in 8 out of 9 trials and provided a number of clear examples of the stimuli.

4.2.4.4 Filter rejection rate

The filter used in the UCAST-FW setting for this study was a 10th order Butterworth filter, which had a rejection rate of 60 dB per octave. This rejection rate used in this study was lower than that used by McGaffin (2007) and slightly higher than the one used by Heidtke (2010). This was to reduce the phase distortion created by a high rejection rate, while maintaining the difficulty of the task. The high slope reduced the possibility that acoustic energy at 2000 Hz and above was audible by some participants, making it a more sensitive measure of auditory processing ability, and one that was less likely to be influenced by the participant's hearing sensitivity above 1000 Hz.

4.2.4.5 Adaptive procedure

Adaptive procedures are those in which the stimulus presented on any one trial depends on the participant's response to stimuli in the preceding one or more trials (Levitt, 1971). In the UCAST-FW, the initial LPF corner frequency of 1000 Hz was adaptively adjusted for subsequent test item presentations. Adaptive procedures are more efficient at finding the threshold than conventional procedures, as they are designed to concentrate stimulus presentations at or near the presumed value of the threshold (Treutwein, 1995). Threshold is typically defined as the stimulus level at which the probability for correct responses is halfway between perfect performance and chance performance (Kaernbach, 2001). In the case of an adaptive forced choice procedure with four alternatives, such as in the UCAST-FW, threshold is defined at the stimulus level where an individual achieves 62.5% positive responses on the psychometric function. This is based on chance performance being 25% and perfect performance being 100%, with 62.5% being halfway between these two extremes.

4.2.4.6 Weighted up-down method

The increment by which the component of the stimulus is either increased or decreased is referred to as a step. The sequence of steps making up a test is referred to as the "adaptive track". Several adaptive algorithms have been proposed to determine the optimal size of the upward and downward steps, each converging to different target probabilities. Currently, staircase procedures and maximum likelihood procedures are the two main categories of adaptive procedures that are commonly used in psychological testing procedures.

In the initial development of the UCAST-FW, McGaffin (2007) used two procedures: the simple up-down staircase procedure of Mackie and Dermody (1986) that converges to the 50% point of the psychometric function; and the transformed up-down staircase method of Levitt (1971) that converges to the 70.7% point of the psychometric function. Kaernbach (1991) suggested that the simple staircase rule does not take into account the effects of chance found in alternative forced choice (AFC) tasks and that its use is not appropriate for tasks involving a high percentage of chance performance. Furthermore, Levitt's (1971) transformed staircase methods, where changes depend on the outcome of two or more of the preceding trials, were designed for 2AFC tasks and are not suitable for use in 4AFC tasks as they are unable to target the 62.5% threshold level (Garcia-Perez & Alcala-Quintana, 2005). As an alternative, Kaernbach (1991) proposed the use of the *weighted* up-down staircase method as it can converge to any desired point on the psychometric function. In addition, the weighted staircase rule has been shown to provide a slightly more accurate and less variable threshold than comparable transformed staircase rules (Garcia-Perez & Alcala-Quintana, 2005). Thus, the weighted up-down procedure was used for the UCAST-FW, as it allows convergence to the desired threshold level of 62.5% for a 4AFC task. As per Kaernbach's 1991 equation, in this study convergence to the 62.5% threshold was achieved by increasing the LPF cut-off frequency by some amount after each incorrect response, and decreasing it by 0.6 of that amount following each correct response.

4.2.4.7 Step size

Two different step sizes were employed in this study. A larger initial step size was used at the start of each set and is referred to as the "initial step size", while a smaller step size was used for the remainder of the set and is referred to as the "working step size". The larger initial step size allowed the adaptive tracking process to quickly converge to near the participant's threshold level, so that when the working step size was implemented to provide a more precise estimate of the participant's true threshold, the filtering was operating close to the participant's true threshold. This setup was implemented in previous research studies using the UCAST-FW, and has been shown to be an advantageous strategy in improving both the accuracy and efficiency of the UCAST-FW (McGaffin, 2007; Heidtke, 2010). In this study the initial increment/decrement step sizes were set at 20.83% and 12.5%; the working increment/decrement step sizes were set at 8.33% and 5%. The transition between the initial and working step phase occurred after five reversals. Each test consisted of a total of 20 reversals – five reversals within the initial phase with larger step sizes, and 15 within the working step phase with smaller step sizes.

4.2.4.8 Obtaining threshold

The 62.5% threshold was obtained by calculating the average of the midpoints between each reversal within the working step phase only. McGaffin (2007) showed that the addition of 5 practice reversals allowed participants to become familiar with the task, without impacting on the final threshold estimate and thus provided more reliable results. Because the adaptive adjustments in filter frequency were percentage changes, rather than a fixed number of Hz, geometric averages were used to calculate midpoints and thresholds, rather than arithmetic averages. Similarly, a log transformation was used in the calculation of the 99% confidence interval of the threshold estimate.

4.2.4.9 Presentation level

Test items were presented at 65 dB Sensation Level (SL) above the participant's pure tone average at 250, 500 and 1000 Hz. This ensured that the presentation level of the low passed frequency components were well above the participants' hearing thresholds, avoiding any effect of audibility on test performance.

The UCAST-FW software used an inverse filter process to compensate for the frequency response of the Sennheiser HD 215 supra-aural headphones and the InSync Buddy USB 6G soundcard used in the study. The frequency response of the headphone and soundcard were measured using a Brüel & Kjær Type 4128 Head and Torso Simulator (HATS) connected to a Brüel & Kjær 7539 5/1-ch. Input/Output Controller Module. The inverse filter process enabled computational estimates of sound level to be made for each combination of stimulus file, filter setting, soundcard, and headphone, and ensured that the output level of each presentation was able to be kept constant despite the different low-pass filter frequencies.

4.2.4.10 Binaural practice run

McGaffin (2007) reported a significant improvement in the low-pass filter threshold obtained with increasing experience with the UCAST-FW, indicating a significant learning effect. This effect was still evident when a short binaural practice run consisting of one initial and 12 working reversals was administered. Heidtke (2010) therefore incorporated a long binaural practice run terminating after five initial and 20 working reversals to minimise learning effects before commencing the monaural testing. That study reported that following the initial practice run, no significant overall improvement in the low-pass filter threshold was found with increased experience with the task. Therefore, an initial long binaural practice run (five initial and 15 working reversals) was administered in this study before assessing left and right ears separately, to minimise the learning effect documented by McGaffin (2007).

4.2.4.11 UCAST-FW settings

Each participant was seated in front of the touch screen at an appropriate height and distance that allowed for comfortable viewing and selection of test items displayed on the screen. Participants were first requested to enter their first name, surname and date of birth into the 'Subject' window as shown in Figure 3. These details were saved with every set of results in order to identify each participant's stored test results. The examiner calculated and entered the participant's pure tone average (at 250, 500 and 1000 Hz) in the provided space, to allow the software to calculate the presentation level suitable for each participant.

As discussed above, a long binaural practice run was initially administered to minimise learning effects on monaural threshold estimations. Left and right ears were subsequently tested in a randomised order. Five different sets of the NU-CHIPs test items were available for selection. These included the four NU-CHIPS word lists (Book A List 1, Book A List 2, Book B List 1, Book B List 2) and a fifth option of all 200 test items included in the four NU-CHIPS word lists. Book A List 1 was always selected for the binaural practice run, Book B List 1, was used for the first monaural test ear, and Book B List 2 was used for the second monaural test ear.

The following instructions were given to each participant prior to starting the test: "*Shortly, I will place these headphones over your ears. Through the headphones, you will hear a female's voice saying a single word, for example "dog". The word may sound muffled. Once you hear the word, four words will appear on this screen. Your task is to select the word that matches the word you heard through the headphones - you can either touch the screen or use the mouse to make your selection. At times the word may be very difficult to* *understand, however even if you are unsure of the word you heard, take a guess. Once you have selected a word the next word will be presented through the headphones, until the program signals the end. You will hear the female's voice in both ears for a start, and then we will test each ear separately. Do you have any questions?*" After the examiner was confident that the participant had understood the task, the following instructions were provided to the participant: "*When you are ready to begin, select the "START" button on the screen and the test will begin.*"

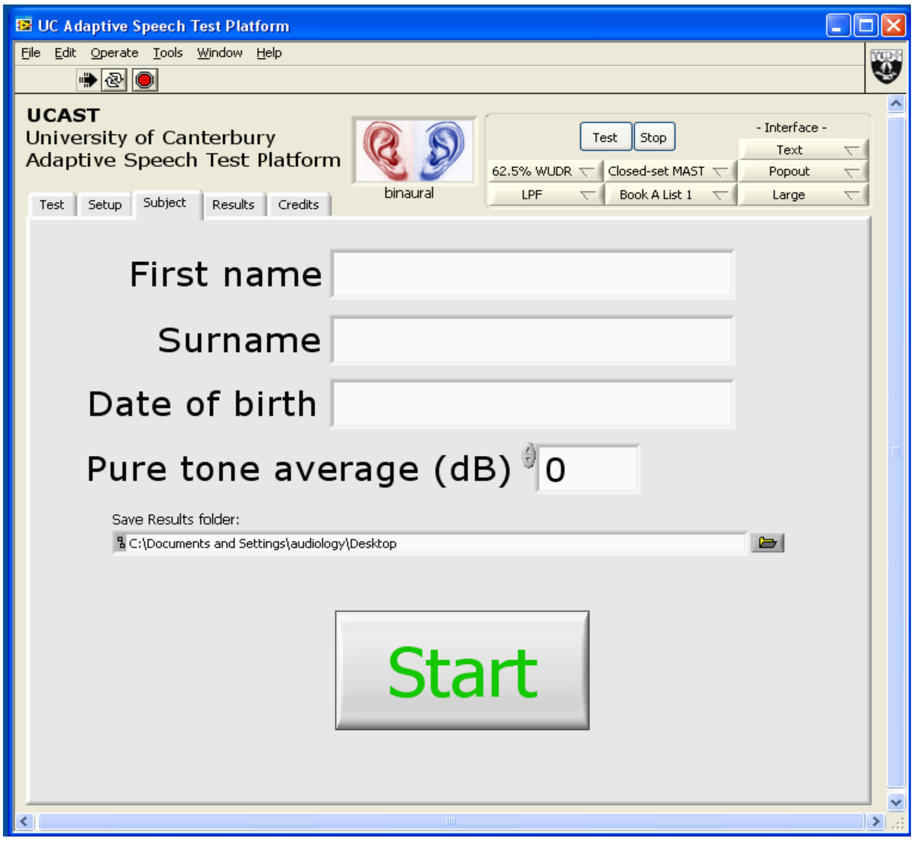

Figure 3. A screenshot of the UCAST-FW "Subject" details screen. The participant's first name, surname, date of birth and pure tone average (at 250, 500 and 1000Hz) were entered.

4.2.4.12 Data acquisition

The UCAST-FW software automatically recorded each response made. An example of an adaptive track from one of the participants is shown in Figure 4. The software also stored the low-pass filter corner frequency used and time taken during each trial, as well as the total number of trials needed to complete each test. The software automatically calculated the participant's final threshold estimates, along with the 99% confidence interval for the final threshold estimate of each set. This automated recording method removed any examiner bias or error in recording participant's responses and calculating their final threshold. All the data was saved to tab-delimited text files.

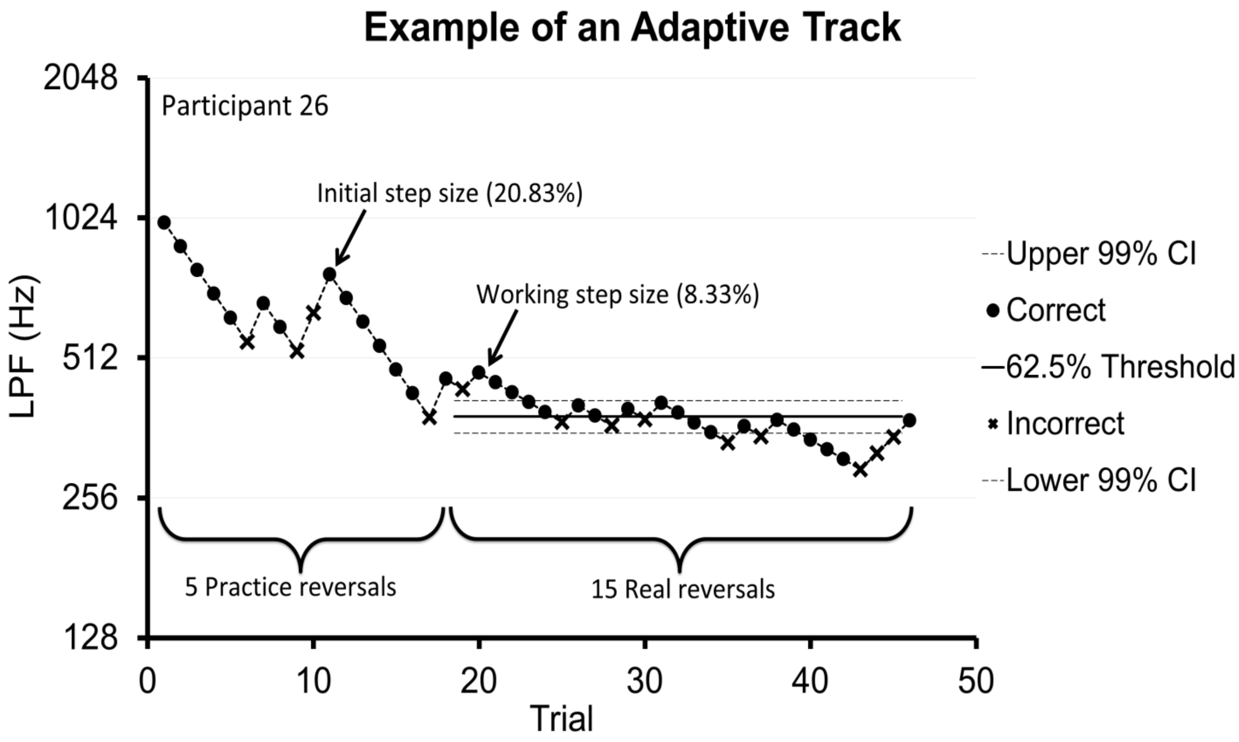

Figure 4. An example of an adaptive track of the right ear of one of the participants from the HFHL group. The measured 62.5% threshold of 382 Hz took 4 min 36 s (46 trials) to obtain.

5 Results

5.1 Effects of peripheral hearing loss on the UCAST-FW score

Table 3 displays individual raw UCAST-FW scores for the binaural practice run, and the right and left monaural runs. The mean Log UCAST-FW scores for the right and left ears for the HFHL group and the NH group are displayed graphically in Figure 5. Error bars depicting 1 standard deviation are also shown. The Mann-Whitney Rank Sum non-parametric test was used to determine whether the NH and HFHL groups differed on the UCAST-FW scores. Non-parametric tests were used as the sample collected failed normality and equal variance tests. The significance level was set at $p \leq .05$. Results revealed no significant difference between the HFHL and the NH groups for either the monaural right ear UCAST-FW scores (U = 159.0, p = 0.727) nor the left ear UCAST-FW scores (U = 172.0, p = 0.988).

Pearson's correlations were completed to determine the relationship between the participants' UCAST-FW scores and their high frequency pure tone thresholds. A weak correlation was found between the right ear UCAST-FW score and the right ear HFPTA (r = -0.0234, p = 0.891), as well as between the right ear UCAST-FW and the right ear 2 kHz threshold (r = 0.193, p = 0.252), 4 kHz threshold (r = 0.00601, p = 0.972), and 8 kHz threshold (r = -0.123, p = 0.468). Similarly, a weak correlation was also noted between the left ear UCAST-FW score and the left ear HFPTA (r = -0.126, p = 0.456), 2 kHz threshold (r = -0.231, p = 0.170), 4 kHz threshold (r = -0.0510, p = 0.764) and 8 kHz threshold (r = -0.0925, p = 0.586). Figures 6 – 9 display scatterplots of individual right and left ear Log UCAST-FW score as a function of HFPTA, 2 kHz, 4 kHz, and 8 kHz thresholds respectively.

Table 3. Individual UCAST-FW scores for the binaural practice run (PR), right ear (RE), and left ear (LE) of participants from both the Normal Hearing (NH) group and the High Frequency Hearing Loss (HFHL) groups.

NH Group (n=18)				**HFHL Group (n=19)**			
Subject	PR	RE	LE	Subject	PR	RE	LE
1	431 Hz	279 Hz	359 Hz	19	472 Hz	332 Hz	236 Hz
2	420 Hz	555 Hz	373 Hz	20	946 Hz	497 Hz	370 Hz
3	570 Hz	538 Hz	740 Hz	21	496 Hz	409 Hz	412 Hz
4	406 Hz	379 Hz	415 Hz	22	352 Hz	402 Hz	365 Hz
5	471 Hz	384 Hz	294 Hz	23	464 Hz	382 Hz	335 Hz
6	378 Hz	409 Hz	400 Hz	24	470 Hz	337 Hz	327 Hz
7	415 Hz	316 Hz	327 Hz	25	427 Hz	380 Hz	377 Hz
8	422 Hz	373 Hz	283 Hz	26	415 Hz	382 Hz	436 Hz
9	351 Hz	451 Hz	417 Hz	27	405 Hz	368 Hz	436 Hz
10	365 Hz	349 Hz	359 Hz	28	464 Hz	397 Hz	405 Hz
11	428 Hz	354 Hz	194 Hz	29	268 Hz	337 Hz	261 Hz
12	467 Hz	376 Hz	360 Hz	30	419 Hz	177 Hz	365 Hz
13	491 Hz	440 Hz	382 Hz	31	376 Hz	444 Hz	523 Hz
14	320 Hz	349 Hz	379 Hz	32	273 Hz	378 Hz	395 Hz
15	456 Hz	424 Hz	477 Hz	33	521 Hz	606 Hz	466 Hz
16	468 Hz	441 Hz	376 Hz	34	399 Hz	302 Hz	317 Hz
17	368 Hz	321 Hz	372 Hz	35	361 Hz	246 Hz	282 Hz
18	449 Hz	225 Hz	390 Hz	36	470 Hz	436 Hz	496 Hz
				37	337 Hz	283 Hz	346 Hz
Mean	426 Hz	387 Hz	383 Hz	Mean	439 Hz	373 Hz	376 Hz
SD	59 Hz	82 Hz	108 Hz	SD	141 Hz	92 Hz	76 Hz

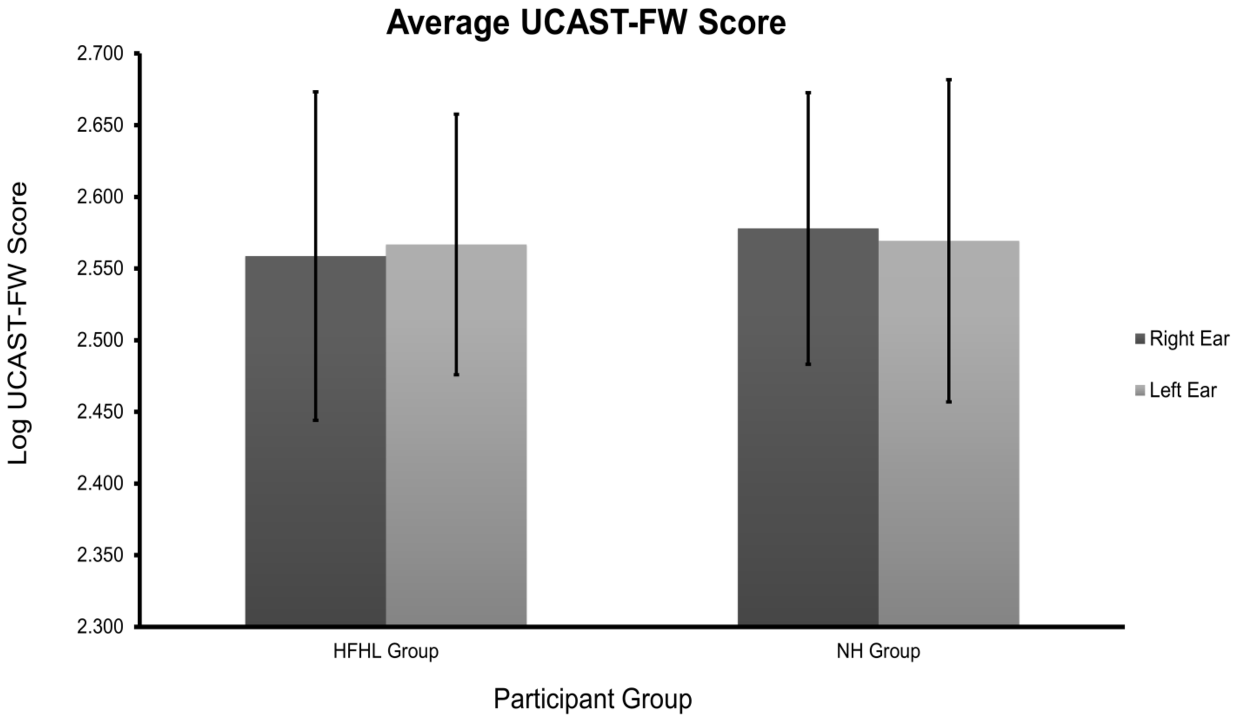

Figure 5. Mean Log UCAST-FW scores of the right and left ears for the High Frequency Hearing Loss (HFHL) group and the Normal Hearing (NH) group. Error bars depicting 1 standard deviation are shown.

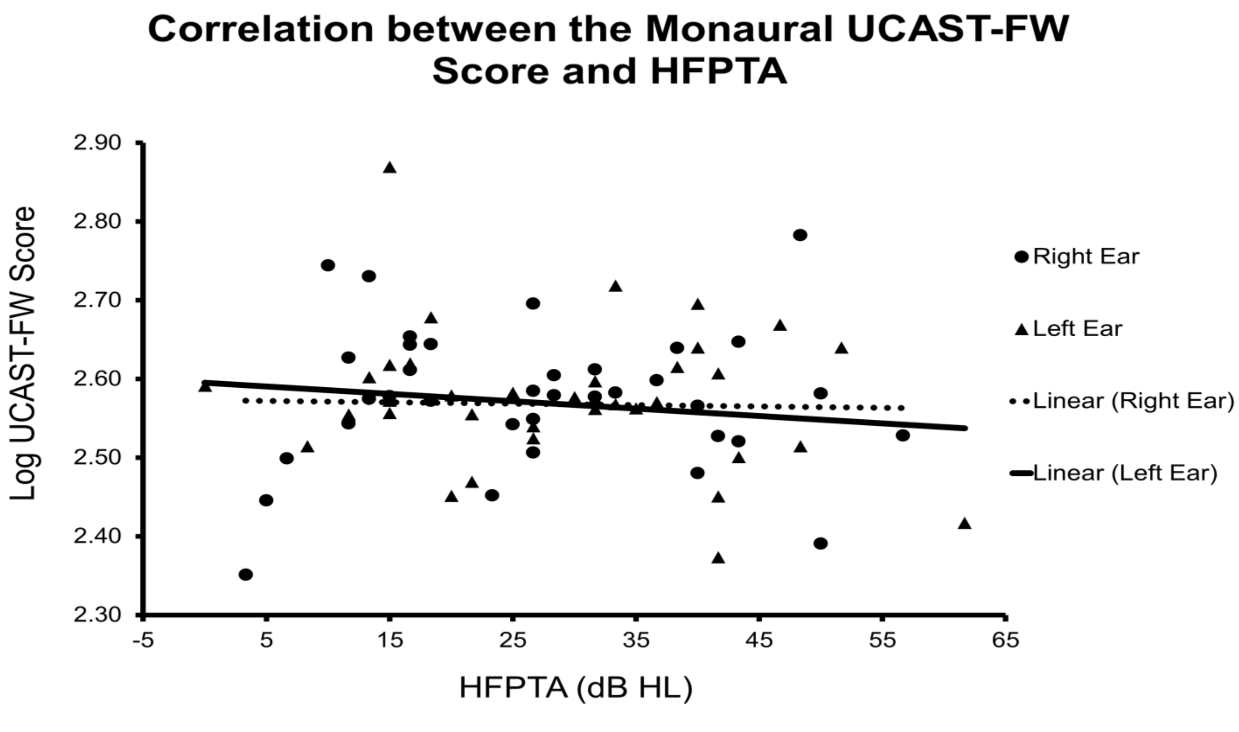

Figure 6. Scatterplots of the monaural Log UCAST-FW score as a function of participant's High Frequency Pure Tone Average (HFPTA) (2, 4, & 8 kHz) in dB Hearing Level (HL) of

the right (circles) and left (triangles) ears. Pearson correlation coefficients (r) for the right and left ear data are -0.0234 (p = 0.891) and -0.126 (p = 0.456) respectively.

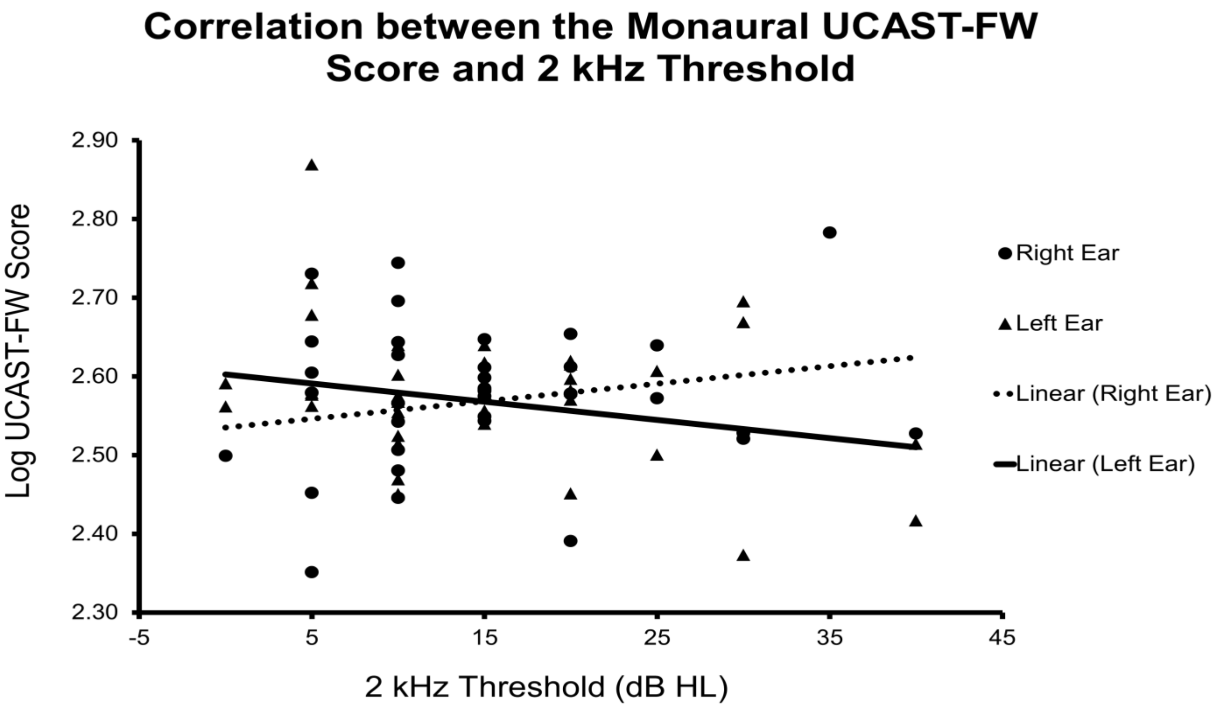

Figure 7. Scatterplots of the monaural Log UCAST-FW score as a function of participant's peripheral hearing threshold at 2 kHz in dB Hearing Level (HL) of the right (circles) and left (triangles) ears. Pearson correlation coefficients (r) for the right and left ear data are 0.193 (p = 0.252) and -0.231 (p = 0.170) respectively.

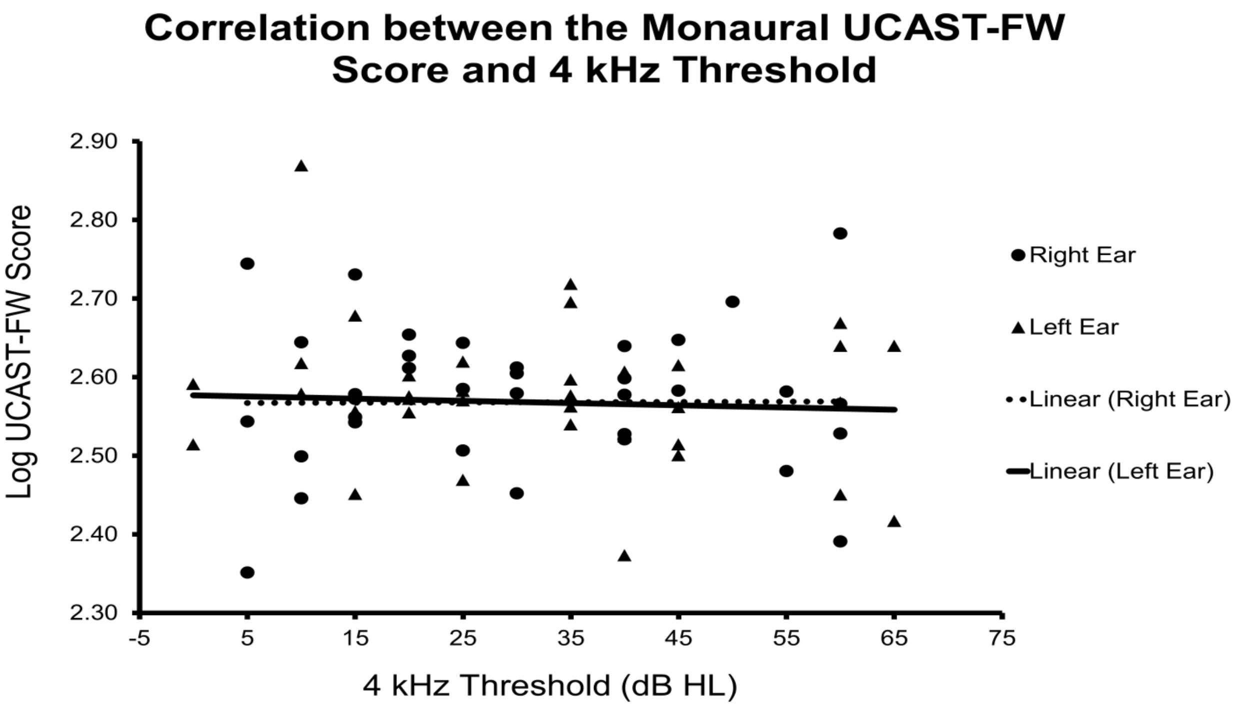

Figure 8. Scatterplots of the monaural Log UCAST-FW score as a function of participant's peripheral hearing threshold at 4 kHz in dB Hearing Level (HL) of the right (circles) and left

(triangles) ears. Pearson correlation coefficients (r) for the right and left ear data are 0.00601 (p = 0.972) and -0.0510 (p = 0.764) respectively.

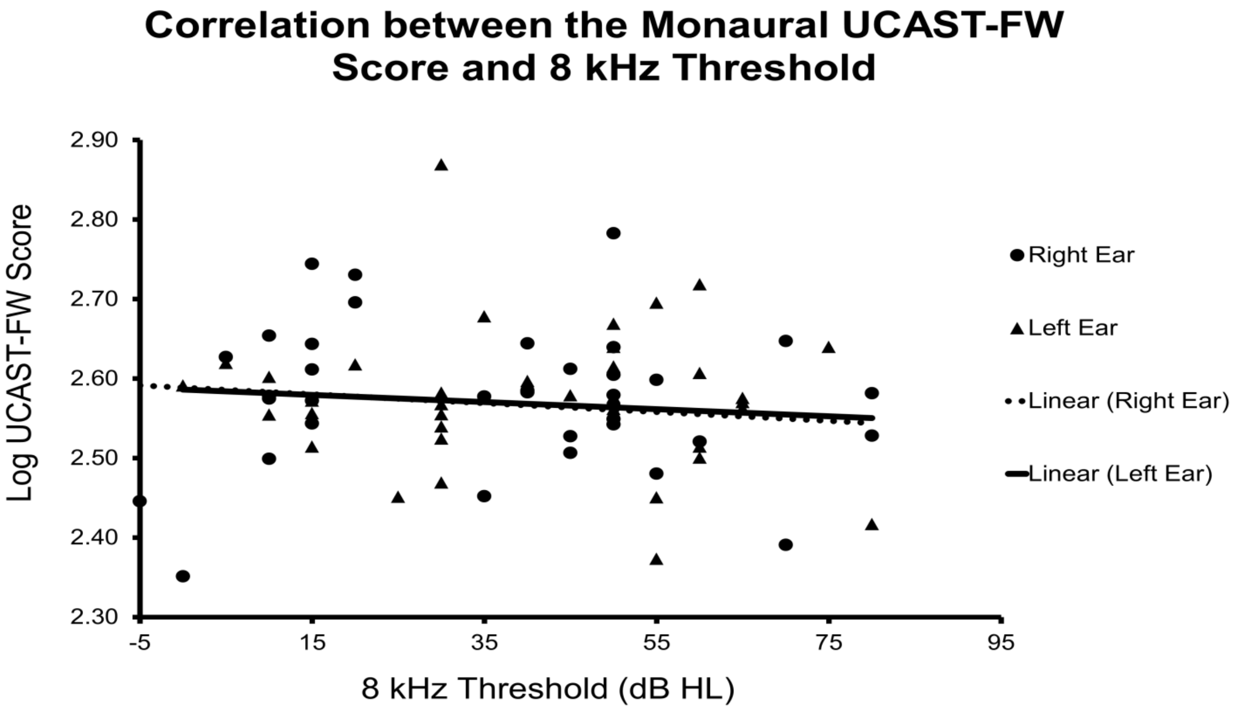

Figure 9. Scatterplots of the monaural Log UCAST-FW score as a function of participant's peripheral hearing threshold at 8 kHz in dB Hearing Level (HL) of the right (circles) and left (triangles) ears. Pearson correlation coefficients (r) for the right and left ear data are -0.123 (p = 0.468) and -0.0925 (p = 0.586) respectively.

5.2 Ear differences

The Wilcoxon Signed Rank test showed no significant difference between the participants' right and left ear monaural UCAST-FW scores (Z = 0.00754, *p* = 1.000).

5.3 Effect of age on test scores

Figure 10 shows a scatterplot of the average monaural UCAST-FW score (i.e. average of the individual right and left ear UCAST-FW score) as a function of age. A very weak correlation was found between the average monaural UCAST-FW score and age (r = 0.0636, *p* = 0.708).

.

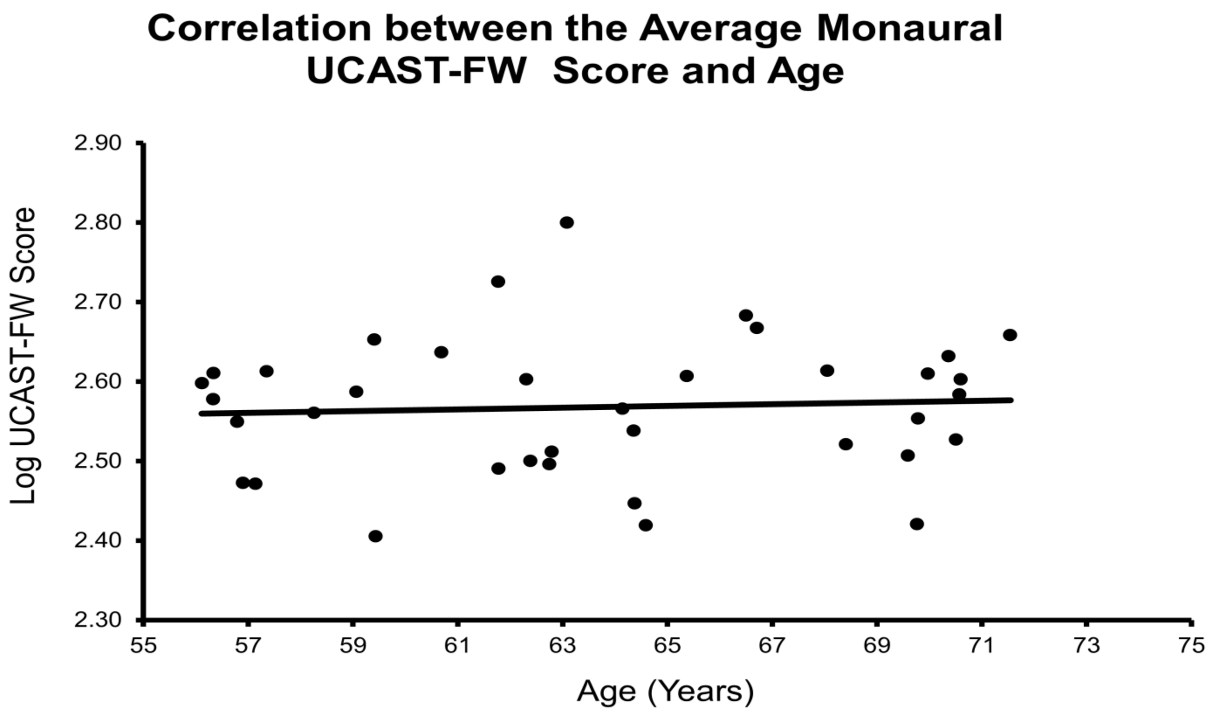

Figure 10. Scatterplot of the average monaural Log UCAST-FW score versus age of all 37 participants.

5.4 Existence of learning effects

For each participant, a long binaural practice run was administered before commencing the monaural testing. Comparison of the participant's UCAST-FW score in the first monaural run to their score obtained in the binaural practice run revealed that of the 37 participants included in this study, 24 showed an average percentage improvement in performance (i.e. a lower low-pass filter cut-off frequency threshold) of 3.6% (±2.8%), with their individual improvements ranging from 0.3% to 13.7%. The remaining 13 participants showed a decrement in the UCAST-FW score of 2.1% (±2.0%), ranging from 0.1% to 6.7%. Comparison of the UCAST-FW score obtained during the first monaural run and the second monaural run showed that a total of 22 participants showed an average improvement in performance on the second monaural run of 3.5% (±3.26%) and ranged from an improvement of 0.5% to 12.2%. On the other hand, 15 participants showed a decrement in performance of 2.5% (±2.1%) and ranged from 0.1% to 6.7%.

The Wilcoxon Signed Rank test showed a significant difference between participant's UCAST-FW score obtained during the binaural practice run and both the first monaural run ($Z = -2.542$, $p = 0.011$) and second monaural run ($Z = 5.303$, $p = <0.001$); however comparison between participant's UCAST-FW score obtained on the first monaural run and the second monaural run revealed no significant difference in performance ($Z = -1.441$, $p = 0.152$).

5.5 Completion time

Participants took an average of 305 seconds (s) (± 95 s), ranging from 229 s to 734 s, to complete the binaural practice run. The first monaural run took an average of 303 s (± 61 s), ranging from 222 s to 444 s, while the second monaural run took on average 310 s (± 80 s) and ranged from 235 s to 551 s. On average participants required a total of 918 s (±202 s) to complete the three UCAST-FW tests administered, and ranged from 698 s to 1537 s. This is equivalent to an average time of 15 minutes and 18 seconds to complete the three tests. The Wilcoxon Signed Rank test showed no significant difference in the time taken to complete the binaural practice run and the time taken to complete the first monaural test (Z = -0.0151, p = 0.994) or second monaural test (Z = 0.737, p = 0.466). No significant difference was found between the time taken to complete the first and second monaural runs (Z = 0.340, p = 0.740). Furthermore, a very weak correlation was found between the average of the time taken for participants to complete the three different runs and their age (r = 0.191, p = 0.259).

5.6 Dichotic Digits Test (DDT) and Random Gap Detection Test (RGDT) results

Table 4 shows the results obtained from the NH group and the HFHL group on both the DDT and RGDT. All 37 participants in this study passed the DDT and RGDT according to published normative data for adult participants (Musiek, 1983; Keith, 2000). The Mann-Whitney Rank Sum test showed no group differences between the DDT scores. However, although all participants passed the RGDT, a significant group difference was noted, indicating that participants in the NH group performed significantly worse on the RGDT than the HFHL group.

A very weak negative correlation was found between the right DDT score and the right HFPTA (r = -0.182, p = 0.282), and a weak negative correlation was obtained between the left DDT score and the left HFPTA (r = -0.292, p = 0.0792). A weak negative correlation was also found between the RGDT gap threshold and the average of the right and left ears HFPTA (r = -0.336, p = 0.0419). No significant correlations were found between the right UCAST-FW score and the right DDT score (r = 0.0272, p = 0.873), the left UCAST-FW score and the left DDT score (r = -0.227, p = 0.176), or between the average monaural

UCAST-FW score and the RGDT score (r = 0.0958, p = 0.573). Comparison between individual's right and left ear DDT scores using the Wilcoxon Signed Rank test showed a significantly greater right ear score (Z = -3.706, p = <0.001).

Table 4. Summary of results obtained from the Dichotic Digits Test (DDT) and the Random Gap Detection Test from both the normal hearing (NH) group and the high frequency hearing loss (HFHL) group. Separate right ear (RE) and left ear (LE) DDT scores are presented. Statistical significance between groups was determined using the Mann-Whitney Rank Sum test.

Test	**Participant group**				**Statistical significance (*p*, *U*)**
	NH Group (n = 18)		HFHL Group (n = 19)		
	RE	LE	RE	LE	
Dichotic Digit Test					
Mean	95.3	92.5	94.6	87.9	*RE:*
Median	97.5	95.0	95.0	87.5	*p* = 0.434; *U* = 145.5
Range	82.5 – 100.0	75.0 – 100.0	87.5 – 100.0	72.5 – 100.0	*LE:*
Standard deviation	5.1	7.3	4.1	7.7	*p* = 0.154; *U* = 124.0
Random Gap Detection Test					
Mean	7.4		5.2		
Median	7.5		4.3		
Range	2.0 – 13.8		2.8 – 8.8		*p* = 0.012*; *U* = 88.0
Standard deviation	2.9		1.9		

*(p < 0.05)

6 Discussion

6.1 Effects of high frequency peripheral hearing loss on the UCAST-FW score

The present study examined the effects of high frequency peripheral hearing loss on the performance of older adults on the UCAST-FW. It was hypothesised that there would be no significant difference in UCAST-FW performance between two groups, differing only in their high frequency hearing profile, and no correlation between the UCAST-FW results and the listener's high frequency peripheral hearing sensitivity. The study findings supported our hypothesis, with participants in both groups showing no significant difference in performance on the UCAST-FW. In addition, correlational analyses revealed negligible correlation between participants' UCAST-FW scores and their high frequency peripheral hearing thresholds. These combined results provide evidence that high frequency peripheral hearing loss, typically seen in the elderly population, has negligible influence on test performance on the UCAST-FW.

Relatively few studies have examined the influence of peripheral hearing loss on test results of low-pass filtered speech tests and those that have, have generally reported that peripheral hearing loss does indeed have an effect on test performance (Miltenberger et al., 1978; Neijenhuis et al., 2004; Cox et al., 2008). The discrepancy in findings between this and past studies may firstly reflect the different parameter settings employed in the filtered speech tests used across studies. Miltenberger et al. (1978) used monosyllabic words passed through a low-pass filter with a fixed cut-off frequency of 500 Hz and a rejection rate of 18 dB per octave. Neijenhuis et al. (2004) used words filtered using a low-pass filter with a fixed cut-off frequency of 500 Hz and a high pass filter with a fixed cut-off frequency of 3000 Hz, both with a slope of 60 dB per octave; while Cox et al. (2008) used words that were low-pass filtered using a fixed cut-off filter frequency set at 750 Hz. In the UCAST-FW, an adaptive algorithm was used to determine the low-pass filter cut-off frequency required by each individual participant in order to obtain a score of 62.5% correct. A rejection rate of 60 dB per octave was employed. In the present study, the average cut-off filter frequency required to obtain the 62.5% threshold was 387 Hz (±82 Hz) and 383 Hz (±108 Hz) for the right and left ears respectively.

The lower the cut-off filter frequency and the higher the rejection rate employed in filtering speech stimuli, the less mid-to-high frequency information remains available to the listener, making the speech stimulus more difficult to discriminate. The UCAST-FW test applied an overall lower cut-off filter frequency and a higher rejection rate when compared to the low-pass filtered tests used by Miltenberger et al. (1978), Neijenhuis et al. (2004) and Cox et al. (2008). As a result, less mid-to-high frequency speech information was made available to listeners, thus reducing the potential contribution of mid-to-high frequency hearing to test performance.

Secondly, though this present study included only participants with a high frequency peripheral hearing loss typical of presbycusis, the three studies described above included participants with differing degrees and configurations of hearing loss. Miltenberger et al. (1978) examined a total of 70 participants (aged between 13 and 65 years) with varying degrees of sensorineural hearing loss. The authors showed that all 16 participants that scored within normal limits on four APD tests administered in the study, including a low-pass filtered test, had essentially normal hearing from 250 Hz to 2000 Hz (i.e. ranged from 0 – 25 dB), whereas their hearing thresholds at 4 and 8 kHz ranged from 0 to 80 dB, with an average hearing threshold of approximately 40 dB at these frequencies. They also reported that the filtered speech score is particularly affected by the degree of hearing loss at 2000 Hz. Neijenhuis et al. (2004) examined 24 participants with a mild, relatively flat, symmetrical peripheral hearing loss, while Cox et al. (2008) examined three groups of participants consisting of 15 participants with normal hearing from 500 to 4000 Hz, 15 participants with a high frequency sloping hearing loss, and 15 participants with both a low and high frequency hearing loss. Findings by Cox et al. (2008) suggested that a mild high frequency sloping hearing loss may not have a significant influence on auditory processing test outcomes, however the presence of a mild to moderate low and high- frequency peripheral hearing loss may significantly alter auditory processing test results. They further suggested that peripheral hearing thresholds at 250 to 2000 Hz are a key predictor of auditory processing test performance. In the present study, though a significant difference was found in the HFPTA between the NH and HFHL group, a significant difference was not found for the 2000 Hz hearing threshold between groups. The 2000 Hz hearing threshold in the HFHL group ranged from a normal to no worse than a mild hearing loss (0 – 40 dB HL), thus supporting the finding by Cox et al. (2008) that such a mild high frequency hearing loss at 2000Hz, may have a negligible influence on test performance. Further studies are required to examine the influence of varying configurations and degrees of peripheral hearing loss on test performance on the UCAST-FW. Given that the UCAST-FW uses a steeply sloping filter and an adaptive algorithm to determine the 62.5% threshold, the cut-off filter frequency that typically results (i.e. around 400 Hz) is so low that very little to no information at 2000 Hz would remain in the signal (e.g. for a UCAST-FW score of 385 Hz, the amount of attenuation of 2 kHz components is around 145 dB). We, therefore predict that the UCAST-FW test performance would not be significantly influenced by a more significant hearing loss at 2000 Hz.

Furthermore, in the present study, all participants had normal hearing between 250 to 1000 Hz and thus the influence of a hearing loss at such frequencies could not be examined. It is not surprising that Miltenberger et al. (1978), Neijenhuis et al. (2004) and Cox et al. (2008) found that a hearing loss in the 250 to 1000 Hz range affected test performance on low-pass filtered speech tests, as the acoustic information of the speech material available after being low-pass filtered is in that frequency range. It follows that we would also expect performance on the UCAST-FW to be influenced by the presence of a low frequency (250 – 1000 Hz) peripheral hearing loss; however further investigation is required to confirm such findings.

Overall, our data provide strong evidence that a high frequency sloping peripheral hearing loss will not significantly impact test performance on the UCAST-FW if the degree of peripheral hearing loss is not more than a mild loss (up to 40 dB HL) at 2 kHz, moderately-severe loss at 4 kHz (up to 65 dB HL) and up to a severe loss at 8 kHz (up to 80 dB HL).

6.2 Ear differences

Findings by McGaffin (2007) showed no significant ear advantage based on monaural UCAST-FW scores for adult participants. These results were supported by findings from this study that also showed no significant difference between the participant's right and left ear UCAST-FW scores. A limitation of the current version of the UCAST-FW program is the inability to provide contralateral masking noise when necessary. In the current study, speech stimuli were presented at 65 dB Sensation Level above the participant's low-frequency pure tone average (LFPTA) at 250, 500 and 1000 Hz. Katz and Lezynski (2002) recommended that an interaural attenuation of 40 dB to be assumed when using supra-aural earphones at all frequencies. Therefore, in the current study, all monaural testing should have incorporated contralateral masking, as the signal may have crossed over to the non-test ear in some cases, thus preventing truly independent testing of each ear. Subsequent versions of the UCAST-FW program incorporate the option of presenting contralateral masking noise to the non-test ear when necessary, in order to prevent cross over hearing and allow the testing of each ear independently.

6.3 Effect of age on test scores

The present study examined the LPF cut-off frequencies at which participants scored 62.5% and revealed no trend between the UCAST-FW scores and age in the group of 37 participants aged between 55 and 71 years that were included in this study. This is contrary to findings by McGaffin (2007), whom examined the LPF cut-off frequencies at which 23 adult participants aged between 18 and 55 years (*M* = 29.8, *SD* = 9.5 years) scored either 50% or 70.7% on the UCAST-FW and reported that performance deteriorated by around 5% with every year of increasing age. One possible reason for this lack of trend is that this study only examined a small age subset, whereas McGaffin (2007) included a wider age range, which would make the presence of any trend more obvious. McGaffin (2007) also used slightly different parameters settings to run the UCAST-FW and assessed a different threshold level as to that used in this study. Furthermore, McGaffin (2007) did not control for cognitive function, which has been shown to decline with increasing age (Sweetow, 2005; Lopez et al., 2003). All participants included in this study passed a cognitive screen, thus cognitive function may have contributed to the observed trend reported by McGaffin (2007).

6.4 Learning effect

The present study included a long binaural practice run consisting of 5 initial and 15 working reversals to reduce any learning effect on test performance. Our results showed a significant difference between the binaural practice run score, when compared to both the first and second monaural runs, but no significant difference between the first and second monaural runs. Similar findings were reported by McGaffin (2007) and Heidtke (2010).

McGaffin (2007) initially carried out a pilot study, which incorporated a short binaural practice run (1 initial reversal and 12 working reversals) and found a significant improvement in performance with increased experience with the UCAST-FW, indicating a significant learning effect. In an expanded study, McGaffin (2007) then incorporated a longer binaural practice run (3 initial and 13 working reversals) and showed that the longer binaural practice run reduced the impact of the learning effect on subsequent monaural test runs, with no significant improvements seen following the first trial. However, McGaffin (2007) recommended the use of an even longer practice run to ensure that a more stable learning plateau is reached before the commencement of monaural testing. A later study by Heidtke (2010) included a long binaural practice run (5 initial and 20 working reversals) and showed no subsequent improvements in performance with increased experience with the UCAST-FW. Our findings support results from McGaffin (2007) and Heidtke (2010) showing the importance of the inclusion of a long binaural practice run when assessing adults to allow any learning effect to plateau before commencing the monaural testing. A binaural practice run comprising of 5 initial and 15 working reversals appeared effective in reducing any learning effect. With the incorporation of a long binaural practice run, a comparison of left and right monaural results can be made without the need to account for the order of testing or the need to apply a correction factor to account for any learning effect.

6.5 Completion time

Results revealed a very weak correlation between the participants' UCAST-FW score and the time they required to complete the test. Participants required an average of approximately 15 minutes (ranged between 12 to 26 minutes) to complete the UCAST-FW. As the UCAST-FW is a computerized and interactive test, adults can be left to complete the task independently, without the need for audiologist supervision. The computer based design of the UCAST-FW allows for automatic scoring, thus eliminating tester bias and scoring errors. Furthermore, the non-verbal four alternative forced choice interface of the UCAST-FW removes subjective evaluation of the participant's response and makes the UCAST-FW suitable for use with participants with significant speech impairments, such as those that may result from a cerebrovascular accident. These factors make the UCAST-FW a relatively quick and easy test to administer and useful across a wide range of participants.

6.6 Limitations and future directions

The current study exhibited three primary limitations that should be taken into account when considering its findings: (1) the as yet undetermined sensitivity and specificity of the UCAST-FW in assessing APD in older adults; (2) the influence of using test material presented in an Australian English accent, rather than a New Zealand English accent; and (3) the influence of cognitive function on the UCAST-FW test performance.

The absence of a gold standard test (i.e. a test with 100% sensitivity and specificity) for APD makes measuring the validity of a particular APD test difficult. As a result, the measurement of validity of any APD test must be viewed in relation to the performance on other APD tests that examine the same auditory function and the use of a comprehensive test battery approach to determine the presence/absence of APD. Heidtke (2010) showed that the UCAST-FW had a significantly higher sensitivity and specificity than two commonly used monaural low-redundancy speech tests, namely the Compressed and Reverberated Words Test (CRWT) and the filtered words subtest of the Screening Test for Auditory Processing Disorder in Children (SCAN-C). However, further research is required to establish the specificity and sensitivity of the UCAST-FW in discriminating between older adults and the elderly with and without APD. Studies comparing performance of a group of older adults with normal auditory processing abilities with a group of adults with auditory processing difficulties as established by performance on a comprehensive APD test battery will help to determine the ability of the UCAST-FW at separating those two groups from one another. It would also be useful to compare performance on the UCAST-FW to currently available low-pass filtered speech tests, such as the filtered words subtest of the SCAN-A. In addition, future research involving a large sample of older adults with normal auditory processing abilities is needed to provide normative data for the UCAST-FW.

Another limitation of the current version of the UCAST-FW that precludes its clinical use in New Zealand at this stage is the lack of four-alternative forced choice test material in New Zealand English. Speech stimuli used in the current version of the UCAST-FW are spoken in an Australian English accent. Accented English can result in alterations of discrete acoustic cues essential for phoneme identity (Gordon-Salant, 2005; Gordon-Salant, Yeni-Komshian & Fitzgibbons, 2010). These alterations can distort the spoken message and make the signal more difficult to perceive (Gordon-Salant, 2005). Gordon-Salant et al. (2010) examined the recognition performance of native English speakers for speech produced by non-native speakers of English whose first language was Spanish. They reported a significant decline in speech understanding performance with accented speech. Although, New Zealand English and Australian English present with similar phonemic systems, there are differences in some phonemes, in particular in the articulation of short vowels (Peters, 2008). Future work is need to develop suitable four-alternative forced choice test material recorded by a native New Zealand English speaker that may then be incorporated into subsequent versions of the UCAST-FW.

Though this study addressed the effects of high frequency peripheral hearing loss on performance on the UCAST-FW, the influence of cognitive deficits remains unknown. Humes (2005) examined the relationship between auditory processing tests and measures of auditory or cognitive function in a total of 213 elderly subjects (aged between 60 to 88 years).

Humes (2005) used a cognitive test battery that included measures of working memory, processing speed for verbal information, and phonological processing. Humes (2005) reported that cognitive function was the most frequently identified predictor of performance on the APD measures used. In addition, Jerger et al. (1989) assessed the auditory and cognitive status in 130 elderly subjects (aged between 51 and 91 years). They reported that 41% of participants presented with cognitive deficits. Of the 65 subjects that were found to have APD, 35 (54%) also showed a concomitant cognitive deficit. Their results suggested that APD and cognitive decline can exist independently in the elderly population, and can both have a significant influence on performance on auditory processing measures. Due to the high prevalence of cognitive deficits in the elderly and the potential influence of cognitive declines on test performance on auditory measures, future research needs to investigate the influence of cognitive function on test performance on the UCAST-FW.

7 Conclusion

Declines in peripheral hearing sensitivity, central auditory processing and cognitive functioning, in isolation or in combination, can lead to presbycusis. Studies have documented the negative effects of peripheral hearing loss and reduced cognitive functioning on performance on currently available APD tests. Due to the high prevalence (which increases with age) of peripheral hearing loss and cognitive impairment in older adults and in the elderly population, the independent assessment and identification of true APD in this population group can be very challenging with currently available APD tests. It is critical to assess and identify the underlying cause of presbycusis in order to provide appropriate and targeted rehabilitation. The main aim of the current study was to investigate the influence of peripheral hearing loss on the UCAST-FW test performance of older adult listeners. The UCAST-FW aimed to eliminate the effect of any high frequency peripheral hearing loss by using low-pass filtered speech material with spectral content almost entirely below 1 kHz. Results showed no significant difference in performance between a group of older adults with normal hearing and a group of older adults with a high frequency hearing loss on the UCAST-FW. Furthermore, no correlation was found between the participant's UCAST-FW score and their high frequency hearing thresholds. These findings suggest that the UCAST-FW can potentially be an effective APD test for the assessment of older adults independent of their high frequency peripheral hearing sensitivity. Findings also showed no significant ear advantage, or any trend between the participant's UCAST-FW score and their age. A binaural practice run comprising of 5 initial and 15 working reversals was effective in reducing any learning effect. The UCAST-FW took an average of 15 minutes to complete, with no correlation found between the completion time and the participant's age. Future developments of the UCAST-FW need to use test materials presented in native New Zealand English to make the test suitable for its use in New Zealand. Further research is needed to investigate the validity of the UCAST-FW in assessing APD in older adults and to determine the influence of cognitive functioning on test performance.

8 Appendices

8.1.1 Appendix 1.1: Advertisement

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HAVING TROUBLE HEARING?

The University of Canterbury Speech Comprehension and Auditory Processing Laboratory is looking for participants for a study to investigate

Effects of High Frequency Hearing Loss on Performance in the University of Canterbury Adaptive Speech Test (UCAST)

We are looking for healthy men and women aged 55 years or over who are native English speaker.

This study will take place at the University of Canterbury Speech & Hearing clinic, Creyke Road, Ilam, Christchurch, New Zealand

This study involves only 1 session of approximately 2 hours duration.

Includes a FREE Hearing Test

PLUS a Petrol voucher for travel expenses

If you are interested and would like more information, please contact

Ali Abu-Hijleh
Phone/TXT: 021 103 1204
Email: ahi28@uclive.ac.nz

Dr Greg O'Beirne
Phone: 03 364 2987 ext. 7085
Email: gregory.obeirne@canterbury.ac.nz

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee
Advertisement Version 1.3, 10/03/2010

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

8.1.2 Appendix 1.2: Advertisement

UC UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

THINK YOU'VE GOT GOOD HEARING?

The University of Canterbury Speech Comprehension and Auditory Processing Laboratory is looking for participants for a study to investigate

Effects of High Frequency Hearing Loss on Performance in the University of Canterbury Adaptive Speech Test (UCAST)

We are looking for healthy men and women aged 55 years or over who are native English speakers with no major hearing problems.

This study will take place at the University of Canterbury Speech & Hearing clinic, Creyke Road, Ilam, Christchurch, New Zealand

This study involves only 1 session of approximately 2 hours duration.

Includes a FREE Hearing Test

PLUS a Petrol voucher for travel expenses

If you are interested and would like more information, please contact

Ali Abu-Hijleh
Phone/TXT: 021 103 1204
Email: ahi28@uclive.ac.nz

Dr Greg O'Beirne
Phone: 03 364 2987 ext. 7085
Email: gregory.obeirne@canterbury.ac.nz

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee
Advertisement Version 1.4, 10/03/2010

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

Auditory Research
Ali - 021 103 1204
ahi28@uclive.ac.nz

8.2.1 Appendix 2.1: Information Sheet

Information Sheet

Department of Communication Disorders
University of Canterbury
Private Bag 4800, Christchurch, 8140
New Zealand

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Research Title:

Effects of High Frequency Hearing Loss on Performance in the University of Canterbury Adaptive Speech Test (UCAST)

Research Student:
Mr Ali Abu-Hijleh
Masters of Audiology Student,
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch, New Zealand
Email: ahi28@uclive.ac.nz
Mobile: 021 103 1204

Primary Supervisor:
Greg O'Beirne, PhD
Senior Lecturer,
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch, New Zealand
Email: gregory.obeirne@canterbury.ac.nz
Phone: (03) 364 2987 Extension: 7085

Co-supervisors:
Natalie Rickard, PhD
Senior Lecturer
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch, New Zealand
Email: natalie.rickard@canterbury.ac.nz
Phone: (03) 3642987 Extension: 3052

Megan McAuliffe, PhD
Senior Lecturer,
Department of Communication Disorders
University of Canterbury
Private Bag 4800
Christchurch, New Zealand
Email: megan.mcauliffe@canterbury.ac.nz
Phone: (03) 364 2987 Extension: 7075

INFORMATION

Introduction and aim of the project:

You are invited to participate in a research project that evaluates the effects of high frequency hearing loss on performance in the University of Canterbury Adaptive Speech Test (UCAST). The aim of this project is to investigate whether the UCAST can be used for the assessment of central auditory processing disorders in adults, independent of any degree of high frequency hearing loss that the person may have.

Participant selection:

Upon your consent, you will be selected for this study if you are an adult (aged 18 years or over), are a native English speaker, with normal cognition and have normal hearing sensitivity in the low frequencies (up to 1000 Hz). The study will require 1 session of approximately 2 hours duration.

The research procedure:

The research will take place at the University of Canterbury Speech & Hearing clinic. If you agree to participate in the study, the following will occur:

1. You will be given an appointment and asked to come to the University of Canterbury Speech & Hearing clinic.
2. After signing the consent form, you will be asked some questions regarding your hearing and general health.
   (Time required: 5-10 minutes).
3. You will have your outer ear and eardrum visually inspected using an otoscope (a specialised ear torch) to determine ear health.
   (Time required: 1 minute).
4. A traditional diagnostic hearing test will be completed to determine your eligibility for the study. This will comprise:
   a. *Pure-tone Audiometry:* This involves establishing your hearing sensitivity thresholds at a range of different frequencies. To do this, you will be seated in a sound booth. Stimuli will be presented through headphones or insert ear

phones at variable intensities. You will be asked to a press a button every time you hear a tone.

b. *Speech Audiometry:* This involves assessing your word recognition using standardised word lists. You will listen to words presented through headphones or insert earphones at variable intensities. You will be asked to verbally repeat the words you hear.
(Time required: 20-30 minutes).

Should a hearing loss be detected in the low frequency range (below 1000Hz), you will not be eligible to participate in the study. However, you will be offered an appointment for a comprehensive hearing test at the University of Canterbury Speech and Hearing Clinic at no charge.

5. A cognitive screening assessment to assess your general cognitive function will be administered. You will be asked to answer questions (e.g., what day is it?), do simple maths, and follow instructions. If you find this task very difficult we will discontinue the assessment and (if you give your consent) will write a letter of referral to your general practitioner.
(Time required: 10 minutes).

6. If you are eligible to participate in the study you will undergo the following tests of auditory processing.
   a. *Dichotic Digits Test:* You will be asked to repeat numbers that are presented simultaneously to each ear via headphones or insert earphones.
   (Time required: 10 minutes).
   b. *Random Gap Detection:* You will be asked to listen to a series of beeps presented via headphones or insert ear phones, and then say how many beeps were heard in each series.
   (Time required: 10 minutes).
   c. *University of Canterbury Adaptive Speech Test (UCAST):* You will be seated in front of a computer. Headphones or insert earphones will be placed over your ears. Recordings of words of varying intelligibility will be presented verbally through the earphones. As each word is presented acoustically, four images will be presented visually on a computer display – of which one image

will match the acoustically presented word. You will be asked to choose the image that you think matches the acoustically presented word, using a computer mouse to select the image on the computer display. This procedure will repeat itself until your thresholds is established. A practice session will precede the actual testing to help familiarise you with the task.
(Time required: 5-10 minutes).

Results:

Test results will be verbally explained after the completion of the tests. If applicable, a follow-up appointment will be made at no charge and appropriate referrals will be made. A written report will also be provided.

The results of the study may be presented at professional audiological conferences and published, but results will be totally anonymous and will not include any personal details of the participants.

Complete confidentiality will be assured of all collected data gathered in this study. To ensure confidentiality all collected data will be stored in a locked filling system within the Communication Disorders Department. Results obtained from the UCAST will be stored on a computer, and will be password protected. Only those individuals directly involved in this study will be able to access this data.

Withdrawal:

Your participation in this study is voluntary (your choice) and you can withdraw from the study at any time. You may also withdraw any information provided within 60 days from completing the study. This will in no way affect any future interactions you may have with the University of Canterbury or services it provides.

Questions:

The project is being carried out as a requirement for a Masters of Audiology by Ali Abu-Hijleh under the supervision of Greg O'Beirne, Natalie Rickard and Megan McAuliffe. We will be pleased to provide any further information about the study and discuss any concerns you may have about participation in the study.

The project has been reviewed ***and approved*** by the University of Canterbury Human Ethics Committee.

8.3.1 Appendix 3.1: Consent Form

Consent Form

Department of Communication Disorders
University of Canterbury
Private Bag 4800, Christchurch, 8140
New Zealand

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Research Title:

Effects of High Frequency Hearing Loss on Performance in the University of Canterbury Adaptive Speech Test (UCAST)

Research Student: Mr Ali Abu-Hijleh

Supervisor: Dr Greg O'Beirne

Co-supervisor: Dr Natalie Rickard
Dr Megan McAuliffe

I have read and I understand the description and requirements of the above-mentioned study, as outlined in the information sheet (dated 17 March 2010). I have had the opportunity to discuss this study and I am satisfied with the answers I have been given. On this basis, I agree to participate in this study, and I consent to publication of the results of the study with the understanding that confidentiality will be preserved.

I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time. I understand that if I choose to withdraw from the study, I may also withdraw all information that I have provided.

I note that the project has been reviewed ***and approved*** by the University of Canterbury Human Ethics Committee.

NAME (please print): ________________________________

Signature: ____

Date: ____

8.2.2 Appendix 4.1: Human Ethics Approval

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Human Ethics Committee
Tel: +64 3 364 2241, Fax: +64 3 364 2856, Email: human-ethics@canterbury.ac.nz

Ref: HEC 2010/31

7 April 2010

Ali Abu-Hijleh
Department of Communication Disorders
UNIVERSITY OF CANTERBURY

Dear Ali

The Human Ethics Committee advises that your research proposal "Effects of high frequency hearing loss on performance in the University of Canterbury Adaptive Speech Test (UCAST)" has been considered and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 6 April 2010.

Best wishes for your project.

Yours sincerely

pp

Dr Michael Grimshaw
Chair, Human Ethics Committee

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

9 References

American Speech-Language Hearing Association (ASHA) (2005). *Common causes of hearing loss in adults.* Retrieved from http://www.asha.org/public/hearing/disorders/causes_adults.htm.

American Speech-Language-Hearing Association. (1996). Central Auditory Processing: Current Status of Research and Implications for Clinical Practice Task Force on Central Auditory Processing Consensus Development. *American Journal of Audiology, 5*(2), 41-52.

Arlinger, S. (2003). Negative consequences of uncorrected hearing loss - A review. *International Journal of Audiology, 42*(SUPPL. 2), 2S17-12S20.

Bamiou, D. E., Liasis, A., Boyd, S., Cohen, M., & Raglan, E. (2000). Central auditory processing disorder as the presenting manifestation of subtle brain pathology. *Audiology, 39*(3), 168-172.

Baran, J. A. (2002). Managing auditory processing disorders in adolescents and adults. *Seminars in Hearing, 23*(4), 327-335.

Bocca, E., & Calearo, C. (1963). Central hearing processes. In J. Jerger (Ed.), *Modern developments in audiology* (pp. 337-370). New York: Academic Press.

Bocca, E., Calearo, C., & Cassinari, V. (1954). A New Method for Testing Hearing in Temporal Lobe Tumours: Preliminary report. *Acta Oto-laryngologica, 44*(3), 219-221.

Bocca, E., Calearo, C., Cassinari, V., & Migliavacca, F. (1955). Testing “Cortical” Hearing in Temporal Lobe Tumours. *Acta Oto-laryngologica, 45*(4), 289-304.

Boothroyd, A., & Nittrouer, S. (1988). Mathematical treatment of context effects in phoneme and word recognition. *Journal of the Acoustical Society of America, 84*(1), 101-114.

Bornstein, S. P., Wilson, R. H., & Cambron, N. K. (1994). Low- and high-pass filtered Northwestern University Auditory Test No. 6 for monaural and binaural evaluation. *Journal of the American Academy of Audiology, 5*(4), 259-264.

British Society of Audiology (2007). *Audiotry Processing Disorder (APD) Steering Committee - Interim position statement on APD.* Retrieved from http://www.thebsa.org.uk/apd/BSA_APD_Position_statement_Final_Draft_Feb_2007.pdf.

Calearo, C., & Antonelli, A. R. (1963). "Cortical" hearing test and cerebral dominance. *Acta Oto-laryngologica, 56*, 17-26.

Carhart, R., & Jerger, J. F. (1959). Preferred method for clinical determination of pure-tone thresholds. *Journal of Speech and Hearing Disorders, 24*(4), 330.

Committee on Hearing and Bioacoustics and Biomechanics (CHABA) (1988). Speech understanding and aging. *Journal of the Acoustical Society of America, 83*(3), 859-895.

Cooper, J. C., & Gates, G. A. (1991). Behavioral audiology. Hearing in the elderly - the Framingham cohort, 1983-1985: Part II. Prevalence of central auditory processing disorders. *Ear and Hearing, 12*(5), 304-311.

Cox, C. L., McCoy, S. L., Tun, P. A., & Wingfield, A. (2008). Monotic auditory processing disorder tests in the older adult population. *Journal of the American Academy of Audiology, 19*(4), 293-308.

Demanez, J. P., & Demanez, L. (2003). Anatomophysiology of the central auditory nervous system: Basic concepts. *Acta Oto-Rhino-Laryngologica Belgica, 57*(4), 227-236.

Divenyi, P. L., Stark, P. B., & Haupt, K. M. (2005). Decline of speech understanding and auditory thresholds in the elderly. *Journal of the Acoustical Society of America, 118*(2), 1089-1100.

Elliot, L. L., & Katz, L. (1979). *Development of northwestern university children's perception of speech (NU-CHIPS) test.* St. Louis: Auditec.

Etzioni, D. A., Liu, J. H., Maggard, M. A., & Ko, C. Y. (2003). The Aging Population and Its Impact on the Surgery Workforce. *Annals of Surgery, 238*(2), 170-177.

Farrer, S. M., & Keith, R. W. (1981). Filtered word testing in the assessment of children's central auditory abilities. *Ear and Hearing, 2*(6), 267-269.

Fifer, R. C., Jerger, J. F., & Berlin, C. I. (1983). Development of a dichotic sentence identification test for hearing-impaired adults. *Ear and Hearing, 4*(6), 300-305.

Flowers, A., Costello, M.R., & Small, V. (1970). *Manual for flowers-costello test of central auditory abilities.* Dearborn: Perceptual Learning Systems.

Frisina, D., & Frisina, R. D. (1997). Speech recognition in noise and presbycusis: Relations to possible neural mechanisms. *Hearing Research, 106*(1-2), 95-104.

García-Pérez, M. A. (1998). Forced-choice staircases with fixed step sizes: asymptotic and small-sample properties. *Vision Research, 38*(12), 1861-1881.

García-Pérez, M. A., & Alcalá-Quintana, R. (2005). Sampling plans for fitting the psychometric function. *Spanish journal of psychology, 8*(2), 256.

Gates, G. A., & Rees, T. S. (1997). Hear ye? Hear ye! Successful auditory aging. *Western Journal of Medicine, 167*(4), 247-252.

Gates, G. A., Cooper Jr, J. C., Kannel, W. B., & Miller, N. J. (1990). Hearing in the elderly: The Framingham cohort, 1983-1985. Part I. Basic audiometric test results. *Ear and Hearing, 11*(4), 247-256.

Golding, M., Taylor, A., Cupples, L., & Mitchell, P. (2006). Odds of demonstrating auditory processing abnormality in the average older adult: The blue mountains hearing study. *Ear and Hearing, 27*(2), 129-138.

Gordon-Salant, S. (2005). Hearing loss and aging: New research findings and clinical implications. *Journal of Rehabilitation Research and Development, 42*(4 SUPPL. 2), 9-24.

Gordon-Salant, S., Yeni-Komshian, G. H., & Fitzgibbons, P. J. (2010). Recognition of accented English in quiet by younger normal-hearing listeners and older listeners with normal-hearing and hearing loss. *Journal of the Acoustical Society of America, 128*(1), 444-455.

Heidtke, U. (2010). *Diagnosis of Auditory Processing Disorder in children using an adaptive filtered speech test.* Unpublished Thesis, University of Canterbury, Christchurch.

Hinchcliffe, R. (1962). The anatomical locus of presbycusis. *The Journal of speech and hearing disorders, 27*, 301-310.

Humes, L. (2009). *Issues in the assessment of auditory processing in older adults.* In Cacace, A., & McFarland, D. Controversies in central auditory processing disorder (pp. 121-150). San Diego: Plural Publishing Inc.

Humes, L. E. (1996). Speech understanding in the elderly. *Journal of the American Academy of Audiology, 7*(3), 161-167.

Humes, L. E. (2005). Do 'auditory processing' tests measure auditory processing in the elderly? *Ear and Hearing, 26*(2), 109-119.

Humes, L. E., & Roberts, L. (1990). Speech-recognition difficulties of the hearing-impaired elderly: The contributions of audibility. *Journal of Speech and Hearing Research, 33*(4), 726-735.

Humes, L. E., Watson, B. U., Christensen, L. A., Cokely, C. G., Halling, D. C., & Lee, L. (1994). Factors associated with individual differences in clinical measures of speech recognition among the elderly. *Journal of Speech and Hearing Research, 37*(2), 465-474.

Jerger, J. (1960). Audiological manifestations of lesions in the auditory nervous system. *Transactions. American Urological Association. Southeastern Section, 1960*, 292-300.

Jerger, J., & Musiek, F. (2000). Report of the consensus conference on the diagnosis of auditory processing disorders in school-aged children. *Journal of the American Academy of Audiology, 11*(9), 467-474.

Jerger, J., Jerger, S., & Pirozzolo, F. (1991). Correlational analysis of speech audiometric scores, hearing loss, age, and cognitive abilities in the elderly. *Ear and Hearing, 12*(2), 103-109.

Jerger, J., Jerger, S., Oliver, T., & Pirozzolo, F. (1989). Speech understanding in the elderly. *Ear and Hearing, 10*(2), 79-89.

Johnsson, L. G., & Hawkins Jr, J. E. (1972). Vascular changes in the human inner ear associated with aging. *Annals of Otology, Rhinology and Laryngology, 81*(3), 364-376.

Jorgensen, M. B. (1961). Changes of aging in the inner ear. Histological studies. *Archives of otolaryngology (Chicago, Ill. : 1960), 74*, 164-170.

Kaernbach, C. (2001). Adaptive threshold estimation with unforced-choice tasks. *Perception and Psychophysics*, *63*(8), 1377-1388.

Katz, J., & Lezynski, J. (2002). Clinical Masking. In J. Katz (Ed.), *Handbook of Clinical Audiology* (5 ed.). London: Lippincott Williams & Wilkins.

Keith, R. W. (1994). *SCAN-A: A test for auditory processing disorders in adolescents and adults.* San Antonio, TX: The Psychological Corporation.

Keith, R.W. (2000). SCAN-C Test for Auditory Processing Disorders in Children – Revised. San Antonio, TX: The Psychological Corporation.

Kiessling, J., Pichora-Fuller, M. K., Gatehouse, S., Stephens, D., Arlinger, S., Chisolm, T., . . . Von Wedel, H. (2003). Candidature for and delivery of audiological services: Special needs of older people. *International Journal of Audiology, 42*(SUPPL. 2), 2S92-S2101.

Kirikae, I., Sato, T., & Shitara, T. (1964). A study of hearing in advanced age. *The Laryngoscope*, *74*, 205-220.

Krishnamurti, S. (2007). Monaural low-redundancy speech tests. In F. Musiek & G. Chermak (Eds.), *Handbook of (central) auditory processing disorder. Auditory neuroscience and diagnosis* (Vol. 1). San Diego: Plural Publishing.

Krmpotic-Nemanic, J. (1971). A new concept of the pathogenesis of presbycusis. *Archives of Otolaryngology, 93*(2), 161-172.

Lacroix, P. G., Harris, J. D., & Randolph, K. J. (1979). Multiplicative effects on sentence comprehension for combined acoustic distortions. *Journal of Speech and Hearing Research, 22*(2), 259-269.

Lee, L. W., & Humes, L. E. (1993). Evaluating a speech-reception threshold model for hearing-impaired listeners. *Journal of the Acoustical Society of America, 93*(5), 2879-2885.

Leek, M. R. (2001). Adaptive procedures in psychophysical research. *Perception and Psychophysics, 63*(8), 1279-1292.

Levitt, H. (1971). Transformed up- down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*(2 pt 2), 467-477.

Lopez, O. L., Jagust, W. J., DeKosky, S. T., Becker, J. T., Fitzpatrick, A., Dulberg, C., . . . Kuller, L. H. (2003). Prevalence and classification of mild cognitive impairment in the cardiovascular health study cognition study. *Archives of Neurology, 60*(10), 1385-1389.

Mackie, K., & Dermody, P. (1986). Use of a monosyllabic adaptive speech test (MAST) with young children. *Journal of Speech and Hearing Research, 29*(2), 275-281.

Martin, F., & Clark, J. (1977). Audiologic detection of auditory processing disorders in children. *Ear and Hearing, 3*(3), 140.

Martin, J. S., & Jerger, J. F. (2005). Some effects of aging on central auditory processing. *Journal of Rehabilitation Research and Development, 42*(4 SUPPL. 2), 25-44.

McGaffin, A. (2007). *Development of a monosyllabic adaptive speech test for the identification of central auditory processing disorder.* Unpublished Thesis, University of Canterbury, Christchurch. http://hdl.handle.net/10092/1504

Medwetsky, L. (2002). Central auditory processing testing; a battery approach. In J. Katz (Ed.), *Handbook of Clinical Audiology* (5th ed., pp. 510-524). Philadelphia: Lippincott Williams & Wilkins.

Miltenberger, G. E., Dawson, G. J., & Raica, A. N. (1978). Central auditory testing with peripheral hearing loss. *Archives of Otolaryngology, 104*(1), 11-15.

Moore, D. R. (2006). Auditory processing disorder (APD): Definition, diagnosis, neural basis, and intervention. *Audiological Medicine, 4*(1), 4-11.

Musiek, F. E. (1983). Assessment of central auditory dysfunction: The dichotic digit test revisited. *Ear and Hearing, 4*(2), 79-83.

Musiek, F. E., Bellis, T. J., & Chermak, G. D. (2005). Nonmodularity of the central auditory nervous system: Implications for (central) auditory processing disorder. *American Journal of Audiology, 14*(2), 128-138.

Musiek, F. E., Geurkink, N. A., & Kietel, S. A. (1982). Test battery assessment of auditory perceptual dysfunction in children. *Laryngoscope, 92*(3), 251-257.

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., . . . Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society, 53*(4), 695-699.

Neijenhuis, K., Tschur, H., & Snik, A. (2004). The effect of mild hearing impairment on auditory processing tests. *Journal of the American Academy of Audiology, 15*(1), 6-16.

Noordhoek, I. M., Houtgast, T., & Festen, J. M. (1999). Measuring the threshold for speech reception by adaptive variation of the signal bandwidth. I. Normal-hearing listeners. *Journal of the Acoustical Society of America, 105*(5), 2895-2902.

Peters, P. (2008). Australian and New Zealand English. In H. Momma & M. Matto (Eds.), *A Companion to the History of the English Language*: Blackwell Publishing Ltd.

Pichora-Fuller, M. K., & Singh, G. (2006). Effects of age on auditory and cognitive processing: Implications for hearing aid fitting and audiologic rehabilitation. *Trends in Amplification, 10*(1), 29-59.

Pichora-Fuller, M. K., & Souza, P. E. (2003). Effects of aging on auditory processing of speech. *International Journal of Audiology, 42*(SUPPL. 2), 2S11-12S16.

Portet, F., Ousset, P. J., Visser, P. J., Frisoni, G. B., Nobili, F., Scheltens, P., . . . Touchon, J. (2006). Mild cognitive impairment (MCI) in medical practice: A critical review of the concept and new diagnostic procedure. Report of the MCI Working Group of the

European Consortium on Alzheimer's Disease. *Journal of Neurology, Neurosurgery and Psychiatry, 77*(6), 714-718.

Rintelmann, W. (1985). Monaural speech test in the detection of central auditory disorders. In M. L. Pinheiro & F. E. Musiek (Eds.), *Assessment of central auditory dysfunction* (pp. 173-200). Baltimore: Williams and Wilkins.

Rodriguez, G. P., DiSarno, N. J., & Hardiman, C. J. (1990). Central auditory processing in normal-hearing elderly adults. *Audiology, 29*(2), 85-92.

Schuknecht, H. (1964). Further observation on the pathology of presbyacusis. *Archives of Otolaryngology*, 80, 369-382.

Sincock, B. (2008). *Clinical applicability of adaptive speech testing: A comparison of the administration time, accuracy, efficiency and reliability of adaptive speech tests with conventional speech audiometry.* Unpublished Thesis, University of Canterbury, Christchurch. http://hdl.handle.net/10092/2157

Speaks, C., Niccum, N., & Van Tasell, D. (1985). Effects of stimulus material on the dichotic listening performance of patients with sensorineural hearing loss. *Journal of Speech and Hearing Research, 28*(1), 16-25.

Stach, B. A., Loiselle, L. H., & Jerger, J. F. (1991). Special hearing aid considerations in elderly patients with auditory processing disorders. *Ear and Hearing, 12*(6 SUPPL.), 131S-138S.

Stach, B. A., Spretnjak, M. L., & Jerger, J. (1990). The prevalence of central presbyacusis in a clinical population. *Journal of the American Academy of Audiology, 1*(2), 109-115.

Strickland, E. A., & Viemeister, N. F. (1994). Is useful speech information carried by fibers with high characteristic frequencies? *Journal of the Acoustical Society of America, 95*(1), 497-500.

Strouse, A. L., Hall, J. W., & Burger, M. C. (1995). Central auditory processing in Alzheimer's disease. *Ear and Hearing, 16*(2), 230-238.

Sweetow, R. (2005). Training the adult brain to listen. *The Hearing Journal, 58*(6), 10.

Treutwein, B. (1995). Adaptive psychophysical procedures. *Vision Research, 35*(17), 2503-2522.

Van Rooij, J. C. G. M., & Plomp, R. (1992). Auditive and cognitive factors in speech perception by elderly listeners. III. Additional data and final discussion. *Journal of the Acoustical Society of America, 91*(2), 1028-1033.

Willeford, J. (1977). Assessing central auditory behavior in children: A test battery approach. In R. W Keith (Ed.), *Central auditory dysfunction* (pp. 43-72). New York: Grune & Stratton.

Willott, J. F., Hnath Chisolm, T., & Lister, J. J. (2001). Modulation of presbycusis: Current status and future directions. *Audiology and Neuro-Otology, 6*(5), 231-249.

Wingfield, A., & Tun, P. A. (2001). Spoken language comprehension in older adults: Interactions between sensory and cognitive change in normal aging. *Seminars in Hearing*, *22*(3), 287-301.

Zera, J. (2004). Speech intelligibility measured by adaptive maximum-likelihood procedure. *Speech Communication*, *42*(3-4), 313-328.