SPEECH UNDERSTANDING ABILITIES OF OLDER ADULTS WITH SENSORINEURAL HEARING LOSS

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Abstract

Older adults with sensorineural hearing loss have greater difficulty understanding speech than younger adults with equivalent hearing (Gates & Mills, 2005). This increased difficulty may be related to the influence of peripheral, central auditory processing or cognitive deficits and although this has been extensively debated the relative contribution to speech understanding is equivocal (Working Group on Speech Understanding and Aging, 1988). Furthermore, changes to the speech mechanism that occur as a result of age lead to natural degradations of signal quality. Studies involving hearing impaired listeners have not examined the influence of such naturally degraded speech signals. The purpose of this study was to determine: (1) whether older hearing impaired listeners demonstrate differences in speech understanding ability or perceived effort of listening on the basis of the age of the speaker and the predictability of the stimulus, and (2) whether any individual differences in speech understanding were related to central auditory processing ability. The participants included nineteen native speakers of New Zealand English ranging in age from 60 to 87 years (mean = 71.4 years) with age-related sensorineural hearing loss. Each participant underwent a full audiological assessment, three measures of central auditory processing (the Dichotic Digits Test, the Random Gap Detection Test and the Staggered Spondaic Words Test), and completed a computer-based listening experiment containing phrases of high and low predictability spoken by two groups: (1) young adults (18 – 30 years) and (2) older adults (70 years and above). Participants were required to repeat stimulus phrases as heard, with the researcher entering orthographic transcriptions into the custom-designed computer programme. An Analysis of Covariance (ANCOVA) was used to determine if significant differences existed in percentage words correct scores as a factor of speaker group (young versus older speakers) and stimulus predictability (high predictability versus low predictability phrases), with level of presentation (dB) as a covariate. Results demonstrated that although there were no significant differences in percentage words correct with regards to speaker group as expected, lower scores were achieved for low predictability phrases. In addition, increased listener effort was required when listening to the speech from the older adult group and during the low predictability phrase condition. Positive correlations were found between word understanding scores and tests of dichotic separation, which suggests that central auditory processing deficits contribute to the speech understanding difficulties of older adults. The implications of these findings for audiological assessment and rehabilitation are explored.

Chapter 1. Introduction

1.1 Thesis Overview

The process of communication begins from the day we are born, and although it is automatic for most, it involves a complex skill set beyond simply speaking and listening. For example, the process of hearing requires not only detection of an acoustic signal but also higher cognitive processing that involves the recognition and meaningful interpretation of sound. Communication continues to be fundamental throughout the lifespan, and as a large number of adults develop hearing loss as they age, their ability to communicate is affected.

Presbycusis is a term that refers to the permanent hearing loss that may occur as a result of ageing. The degree of presbycusis can vary from mild to significant impairment (Arlinger, 1991) and it most commonly results in a sloping high frequency sensorineural hearing loss (SNHL). This causes decreased audibility for frequencies which include sounds that are important for speech understanding (Willot, Chisolm & Lister, 2001). However, research has shown that older adults have relatively more difficulty understanding speech than younger listeners with equivalent hearing loss, particularly in listening conditions that are not ideal, such as background noise or reverberation (Gates & Mills, 2005; Gordon-Salant, 2005; Schum, Matthews & Lee, 1991). Research has suggested that although reduced audibility is a factor, some proportion of the speech understanding difficulties reflect changes within the central auditory system (Gates, Feeney & Mills, 2008) or a general decline in cognitive function (Gordon-Salant & Fitzgibbons, 1997) that may occur with increasing age. However, determining the extent of the contribution of peripheral, central auditory and cognitive factors has been problematic (Humes, 2008).

Research on the speech understanding difficulties of older adults with hearing loss has focused on laboratory-based experiments in which the acoustic signal has been degraded using techniques such as time compression or reverberation. It is therefore important to relate the speech understanding difficulties of older adults back to “real world” situations and consider the communicative situations in which older adults are likely to find themselves. It is likely that the primary communicative partners of older adults are also older adults. Research into age-related changes in the speech mechanism have shown that there are a number of perceptual and acoustic features of speech that deteriorate with age, resulting in natural degradations to the acoustic signal (Baum & Bodner, 1983; Ferrand, 2002; Xue & Hao, 2003). It is possible that this may cause older adult listeners to have increased difficulty understanding such speakers in comparison to younger speakers with normal speech. In addition, listener-related aspects such as listener effort and intelligibility for hearing impaired older adults have not received significant research attention.

Further knowledge of the factors influencing the speech understanding difficulties experienced by older adults with hearing loss will enhance the assessment and treatment of such individuals. Assessment of this population continues to focus on pure tone audiometry, but more ecological assessments, including those that evaluate central auditory function, may provide relevant information on the extent of the communication difficulties experienced by the individual. Furthermore, the limited benefit that some individuals report from hearing aids (Kochkin, 2003) may be due to the combined influence of speaker, central auditory and cognitive factors.

1.2 Literature Review

This section begins with a discussion regarding the prevalence, characteristics and impact of age-related hearing loss, including a review of the proposed causes of the speech understanding difficulties experienced by the older adult population. Following this, the discussion focuses on the effects of reduced speaker intelligibility and potential implications on the speech understanding abilities of older adults with hearing loss.

1.2.1 Prevalence of Hearing Loss in Older Adults

Hearing impairment is the third most chronic condition within the ageing population, following arthritis and hypertension (Weinstein, 2002). Although hearing loss in older adults is well documented in large scale studies, there are varying reports on the prevalence of hearing loss within this population. This is concerning as accurate indications of the prevalence of hearing loss would provide information vital for the planning of adequate rehabilitation services, such as the distribution of hearing aids (Sindhusake et al., 2001).

Wilson et al. (1999) reviewed the pure-tone averages (i.e., hearing thresholds at 500, 1,000, 2,000 and 4,000 Hz) of 9,027 Australian participants using surveys and audiological testing. It was reported that the prevalence of moderate hearing loss (45 dB or greater) rose from 2% in the 51 to 60 years group to 2.5% in the 61 to 70 group, to 21.4% in the 70 years and above group. In contrast, Cruickshanks et al. (1998) reported much higher prevalence findings. In a sample of 3,753 adults aged between 48 and 92 years it was reported that 45.9% exhibited hearing loss. Of those with hearing loss, 30.6% were classified as moderately impaired, defined as having a pure tone average (PTA) of between 40 and 60 dB. Overall, these studies indicate that hearing loss affects a significant portion of population, particularly as age increases, and it therefore has the potential to affect quality of life of older adults.

The differing reports on the prevalence of hearing loss are likely due, in part, to the lack of standardised criteria for identifying hearing loss. For example, Cruickshanks et al. (1998) used a criterion of 40 to 60 dB to identify a moderate hearing impairment, whereas Wilson et al. (1999) used 45 to 65 dB. This issue is also salient on review of studies which report differing prevalence figures based on samples from the same cohort. Using the Framingham

Heart Study Cohort (which initially involved 6,015 participants) as a reference, Moscicki, Elkins, Baum and McNamara (1985) undertook audiological tests on 2,293 individuals aged between 58 and 88 years. Pure tone audiometry was used to establish the presence of hearing loss among this group, with a definition of hearing loss being a threshold greater than 20 dB HL at any frequency in any ear. Based on these criteria, the overall prevalence of hearing loss among this population was 83%. In contrast, Gates, Cooper, Kannel and Miller (1990), using the same cohort but with a sample of 1,662 participants and a definition of a PTA of more than 26 dB HL in the better ear, reported a significantly lower prevalence of only 29%.

A second explanation for the varying prevalence reports among older adults may be related to a lack of participation in such studies. This was illustrated by Parving, Biering-Sorensen, Bech, Christensen and Sotrensen (1997) in a study of hearing loss in individuals aged 80 years and above from a total population of 2,915 within a target geographical location. Those who had previously been provided with a hearing aid were selected for the study (*n* = 859). A further 565 individuals without hearing aids were invited to participate, on the basis of being matched with regards to the age and gender distribution of the general population. However, of the second group, only 231 individuals accepted the invitation to participate, which represents 8% of the total participant pool. The most common reasons given for not participating included no perceived hearing problems, individuals felt they were too old or had other conditions that would affect their participation, and an unspecified refusal to participate. The estimated prevalence of hearing loss for those aged 80 years and above was between 33 and 66%; however, the wide range was attributed to insufficient data collection.

1.2.2 Presbycusis

The gradual decrease in hearing ability that frequently occurs with increased age is termed presbycusis. The most common characteristic of presbycusis is decreased hearing sensitivity in both ears, with the typical pattern being a sloping high frequency sensorineural loss, which includes sounds that are most vital for speech perception and understanding (Willott et al., 2001). The degree to which an individual is affected by presbycusis can vary from a mild to a significant impairment (Arlinger, 1991). It has been suggested that the definition of presbycusis should cover all potential causes of hearing loss as a result of age that cannot be attributed to specified pathology, trauma or genetic condition; including deficits within both the peripheral and central auditory system (Gates et al., 1990; Willott, 1991). Therefore, presbycusis not only affects an individual's ability to detect sounds but there are other effects which will be subsequently discussed, such as their ability to understand speech. The Working Group on Speech Understanding and Aging (1988) established that there is an interaction of three distinct processes of physiological deterioration that result in the hearing loss that is categorised as presbycusis. Firstly, deterioration can result from the general decline of function that occurs within the peripheral and central nervous systems, which leads to disruption within the auditory system. Secondly, the hearing loss may be due to the combined effect of inherent factors (or the effects of 'wear and tear') and extrinsic factors (such as those related to trauma). Thirdly, the person's vulnerability to certain diseases can also have a role in the deterioration of hearing.

It has also been found that auditory ageing is not homogeneous throughout the auditory system. Age-related changes in central auditory processing abilities tend to occur more quickly than changes within the peripheral hearing mechanisms. Gates et al. (2008) examined the rate of age-related changes in both the peripheral and central parts of the auditory systems of 241 individuals aged 65 years and over. A comparison of results was made from peripheral tests, tests of central auditory processing and electrophysiological tests of the eighth nerve and central auditory pathway functioning. Central auditory processing was observed to be the area in which decline is greatest over and above changes in pure-tone threshold sensitivity. The tests of outer hair cell function and central auditory pathway functioning reduced the least, showing the smallest age effects (Gates et al., 2008).

1.2.3 Speech Understanding Difficulties of Older Adults with Hearing Loss

The term ‘speech understanding’ has been used in the literature to describe the listener’s ability to perceive the speech signal, whether through discrimination, identification, recognition or comprehension (Humes, 1996). The reduced ability to understand speech has perhaps the greatest effect on overall communication. Interestingly the extent of the speech understanding difficulties experienced by an older individual may not correlate with expectations based on the audiogram alone (Cooper & Gates, 1991; Gates & Mills, 2005; Stach, Spretjak & Jerger, 1990). Certainly, the fact that many older adults experience a hearing loss explains some of the deficit observed in speech understanding. However, these difficulties sometimes occur in the presence of hearing thresholds that are close to normal. This is due, in part, to the fact that pure tone audiometry involves monaural detection of simple tones in a quiet environment. This technique is not reflective of the complex speech signal or factors present in “real-world” listening conditions such as background noise or reverberant environments. However, it has been proposed that a more complex interaction of both peripheral and central auditory deficits may contribute to the increased difficulty in speech understanding experienced by older adults. Specifically, the findings of Gates et al. (2008) indicate that central auditory processing deficits may play a significant role.

The Working Group on Speech Understanding and Aging (1988) reviewed the literature on hearing in older adults and discussed three hypotheses that could explain the individual differences in speech understanding ability noted both clinically and in research studies. These are: 1) the peripheral hypothesis, 2) the central-auditory hypothesis, and 3) the cognitive hypothesis. There is, however, conflicting evidence regarding which factor, or combination of factors, has the biggest impact on speech understanding. Each of these hypotheses will therefore be considered in turn.

1.2.3.1 Peripheral Hypothesis

The peripheral hypothesis poses that the speech understanding difficulties experienced with ageing are primarily associated with age-related changes within the auditory periphery which affect the detection of sound, particularly in the high frequencies (Humes, 1996). The major contributor is the decreased hearing sensitivity that is characteristic of presbycusis (Willot et al., 2001). However other characteristics have also been reported, such as the filtering provided by the listener's loss of sensitivity which results in decreased spectral and temporal resolution (Humes, 1996).

Numerous studies have provided support for the peripheral hypothesis of age-related decline in speech perception. For example, Humes and Roberts (1990) investigated the effects of reduced audibility on monaural and binaural speech recognition in older adults using three groups; young adult normal hearing listeners (n = 13), older adult hearing impaired listeners (n = 13), and young adult normal hearing listeners with a simulated hearing loss (i.e., matched to the older adult hearing impaired group through the use of spectrally shaped masking noise) (n = 10). Speech recognition was measured across three listening conditions: reverberation, background noise and combined reverberation and background noise. Results of the study revealed that the older hearing impaired group demonstrated reduced speech recognition scores in comparison to the young normal hearing group across all conditions. However, similar speech recognition scores were demonstrated by the older hearing impaired group and the young 'masked' group. As the use of masking noise imitated the effect of an SNHL, the results suggest that the major factor contributing to poor speech recognition in the older adult listeners was elevated hearing thresholds; providing support for the peripheral hypothesis. While this was the case, 20% of the individual variance in speech recognition scores could not be attributed to speech recognition scores alone (Humes & Roberts, 1990).

Therefore, a follow-up study aimed to account for the remaining individual variance by examining the affect of hearing loss and ageing on speech identification and auditory processing tasks (Humes & Christopherson, 1991). Participants included the three age groups as in the previous study, however the older hearing impaired group was further divided into 'young old' adults (aged 65 to 75 years) and 'old old' adults (aged 76 to 86 years). Tasks included nonsense syllable identification in three conditions; quiet, band-pass filtered and reverberated. Auditory processing ability was examined using the Test of Basic Auditory Capabilities (TBAC). As in the previous study, analysis revealed that the major predictor of speech identification performance was SNHL; supporting the peripheral hypothesis. However, both older groups demonstrated increased variance and poorer performance in all components of the TBAC than the younger groups, with these deficits most prominent in the 'old old' group. This finding indicated that central auditory abilities may in fact decrease as a function of increasing age, regardless of hearing sensitivity (Humes & Christopherson, 1991).

Support for the peripheral hypothesis has also been obtained from studies involving increased emphasis on non-auditory factors. Jerger, Jerger and Pirozzolo (1991) examined the relationships between age, pure tone hearing thresholds, performance on speech audiometry, and performance on neuropsychological measures in 200 participants aged from 50 to 91 years. The results indicated that the degree of hearing loss affected scores on all five speech audiometric measures, and therefore had the most significant effect on the speech understanding ability of older adults. Cognitive status was also found to have a significant, albeit smaller, effect as it affected performance on two of the five speech measures. Similar findings were observed by van Rooij, Plomp and Orlebeke (1989) following an extensive examination (including tests of audition, speech perception and cognitive tests) of 24 young normal hearing listeners (aged 18 to 28 years) and 24 older adult listeners (aged 61 to 85 years). The findings revealed that 69% of the variance in performance on speech perception tests in the older adult group was accounted for by the degree of hearing loss, particularly in the higher frequencies. Although the older group did exhibit reduced memory capacity and a general slowing of processing speed, these factors did not account for the remaining variance, providing further support for the peripheral hypothesis. Similar results were found in a larger scale study of 72 older adult listeners (aged 60 to 93 years) which was based on a similar test battery and procedure (van Rooij & Plomp, 1990).

The above brief review of studies has shown that there is evidence to suggest that peripheral auditory factors are the primary contributor to the speech understanding difficulties observed in older adults. Clinically, these findings would imply that simply restoring audibility via hearing aids would result in a significant improvement in speech understanding ability. While this is the case for many, it is not always so. It appears that in some cases, central auditory processing and cognitive abilities may also affect the speech understanding ability of older adults. A short overview of the literature in this field will be presented in the following sections.

1.2.3.2 Central-Auditory Hypothesis

Understanding speech is a complex process which requires the interaction of many central auditory processes in order to detect the acoustic signal, locate the source of the sound, recognise phonemes and how they are put together, and to then extract the meaning. The central-auditory hypothesis poses that the difficulties older adults encounter with speech understanding are primarily related to changes, either structural or functional, within the auditory pathway or the auditory areas within the cortex (Humes, 1996). These pathways are thought to be responsible for behavioural phenomena such as auditory discrimination, auditory pattern recognition, performance with degraded signals, auditory closure, aspects relating to temporal processing, binaural integration and separation, and sound localisation (American Speech and Hearing Association [ASHA], 2005).

Although there is no universally accepted definition of what constitutes a central auditory processing disorder (CAPD), it has been proposed that the term describes deficits within the auditory modality that are not a result of dysfunction of other modalities such as cognition, higher order language, or other associated factors (ASHA, 2005). At this higher level, speech understanding is dependent on the interaction of two types of processes; “bottom-up” and “top-down” processes. Bottom-up processing starts at the level of the cochlea and is based on the aspects of the incoming speech signal. Top-down processing is influenced by general cognitive functioning and relates to the use of stored knowledge (such as knowledge of lexical, semantic and grammatical rules) to extract meaning from the signal (Goldstein, 2007). At this level of the brain, speech perception is also influenced by other sensory modalities, such as memory, learning and attention (British Society of Audiology Auditory Processing Disorder Steering Committee [BSA], 2007). Presbycusis may also affect these central auditory processes, as the auditory system attempts to compensate for the reduction in peripheral hearing sensitivity. Common symptoms of central auditory difficulties include poor recognition, discrimination, localisation, separation or ordering of non-speech signals as well as speech sounds (BSA, 2007). In particular, difficulties occur in any situation in which the listening situation is not optimal, such as in the presence of background noise, reverberation or competing speech (Keith, 1999). Individuals with CAPD usually have normal hearing; however, processing issues can be exacerbated as a result of presbycusis, which could partially explain the difficulties in speech understanding experienced by older adults.

Overall, the prevalence of CAPD in the older population appears to be strongly linked with increasing age. Stach et al. (1990) conducted a retrospective analysis of 700 patients aged 50 years and above to study age-related changes in central auditory processing, which they termed ‘central presbyacusis’. In addition, a ‘non-clinical’ sample (*n* = 138) was taken from a group of research volunteers who were not previously identified as hearing impaired. In both groups, results on speech audiometry tests and measures of central auditory processing (for example, the Synthetic Sentence Identification test (SSI) and the PAL PB-50 Word Lists) were used to determine the prevalence of central presbyacusis. It was reported that speech understanding ability worsened with increasing age, as did peripheral hearing loss. Results from the non-clinical group were thought to provide a more representative estimate of central presbyacusis within the general population, as these participants had not actively sought hearing assessment. The prevalence of CAPD within this group increased with age, from 0% in the youngest age group (50 to 54 years), to 72% in the oldest group (80 years and above) (Stach et al., 1990). In contrast, Cooper and Gates (1991) reported a lower prevalence of CAPD in their examination of 1,026 of participants aged 64 to 93 years, recruited from the Framingham Heart Study cohort. The study showed that 22.6% of the subjects met the criteria on any one test, suggesting that the prevalence of CAPD in older adults is lower than previously thought. These studies highlight the variability in terms of reported prevalence of central auditory problems in older adults, which possibly reflects problems within the assessment process such as inconsistencies in the criteria.

Given the link between CAPD and increasing age, it is important to examine the relative contribution of peripheral hearing sensitivity and central auditory processing ability to the speech understanding difficulties experienced by older adults. This was carried out by Jerger, Jerger, Oliver and Pirozzolo (1989) in a study involving 130 participants aged from 51 to 91 years. The test battery included peripheral hearing tests, measures of central auditory processing that were designed to limit the effects of audibility (for example, the SSI, the PB-SSI criterion, the Speech Perception In Noise test and the Dichotic Sentence Identification test) and a number of neuropsychological tests, such as the Minnesota Multiphasic Personality Inventory and the Weschler Adult Intelligence Scale – Revised (WAIS-R). Participants were identified as having CAPD if they scored below test cut-offs on any of the above speech measures. Fifty percent of participants met this criterion. Participants were subsequently divided into two subgroups matched for age, gender and hearing loss; one group with normal cognitive status and one group with abnormal cognitive status in order to observe any interaction between the two. They found that the presence of CAPD does not assume cognitive deficits, as they can occur independently or they can coexist. On this basis, the authors suggested that it is the deficits in central auditory functioning rather than peripheral hearing loss or cognitive factors that account for the difficulties in speech understanding experienced by older adults (Jerger et al., 1989).

Studies involving demanding listening situations have also demonstrated the significant contribution of auditory processing deficits to speech understanding difficulties. For example, Gordon-Salant and Fitzgibbons (1993) used low predictability stimuli in four conditions (undistorted, time compressed, interrupted and reverberated) across four levels of distortion to assess the temporal processing skills of young normal hearing adults, older normal hearing adults (65 to 76 years), young adults with mild to moderate sloping hearing loss and older adults with similar hearing losses. Tests of gap duration and gap detection were also completed. No age effect was apparent in terms of speech recognition in undistorted conditions. However, there were significant effects of age and hearing loss when the signal was time compressed, reverberated or interrupted. It was also noted that as age increased, gap discrimination thresholds increased. The authors concluded that temporal processing deficits are observed in the ageing population, resulting in reduced speech perception scores (Gordon-Salant & Fitzgibbons, 1993). Similar findings were reported in a longitudinal study (over five years) of 29 older adults which assessed pure-tone thresholds, word recognition in quiet, and speech understanding in degraded conditions (such as babble noise and reverberation). Hearing thresholds increased on average by 3.33 dB over the five year period, and there was a significant decrease in performance on all measures, which was consistent with the audiometric findings. Therefore, with regards to communicative abilities, the main effect of the hearing loss was a decline in the ability to understand speech, particularly when the signal is degraded in the presence of background noise or reverberation (Divenyi, Stark and Haupt, 2005).

It remains unclear how much of the speech understanding difficulty experienced by older adults is due to deficits in auditory processing, which is in part due to the contention regarding the definition of CAPD. Researchers have utilised different test batteries, and even those who have used the same tests may have used different pass/fail criteria for identification, which has lead to variation in the estimates of prevalence of CAPD in the older adult population (Humes, 1996). Test interpretation is challenging due to difficulty separating the relative influence of peripheral hearing sensitivity and the influence of other cognitive modalities (Humes, 2008). Due to this difficulty, there is a large body of research devoted to determining the relative contributions of age-related cognitive decline with regards to the speech understanding difficulties in older adults, which will be discussed below.

1.2.3.3 Cognitive Hypothesis

The cognitive hypothesis poses that the speech understanding difficulties experienced by older adults may be influenced by a decline in the general cognitive processes within the cortex that are responsible for sensory modalities other than audition (Humes, 1996). Processes central to speech perception include working memory and attention (BSA, 2007) which may also decline with age. In addition, processing speed has been a topic of research investigation, with a slowing of neural conduction observed in some older adults with hearing loss (Tremblay, Piskosz & Souza, 2003). Although the literature suggests that cognitive decline plays a part in the diminished speech perception abilities of older adults, they do not appear to be the primary influence. For example, as previously mentioned, van Rooij et al. (1989, 1990) determined that cognitive factors such as reduced working memory and slowing of processing speed were found to account for some of the variance in speech perception, albeit to a lesser extent than peripheral factors.

The influence of cognitive factors appears more likely to account for differences observed in speech perception in more challenging listening situations. Studies involving dichotic listening tasks have shown increased cognitive effects in ageing individuals as the demands of the listening situation increase. Hallgren, Larsby, Lyxell and Arlinger (2001) examined such age effects on central auditory abilities (in particular dichotic listening) and cognitive function (working memory capacity, phonological processing and verbal information processing speed) in 15 ‘younger’ (aged 42 to 66 years) and 15 ‘older’ (aged 67 to 84 years) adults with hearing loss. The older group performed significantly worse on all dichotic listening tasks and on cognitive tests (particularly working memory and processing speed); suggesting an age effect. Variations in peripheral function cannot explain the full extent of the variation seen between the age groups; therefore supporting the cognitive hypothesis. Gordon-Salant and Fitzgibbons (1997) altered the demands of the listening situation by comparing performance on both high predictability and low predictability phrase recall tasks, in order to determine whether older adult listeners’ speech understanding was most affected by limitations in working memory, peripheral hearing sensitivity or speech rate. Participants included four groups; young adult normal hearing listeners, older adult normal hearing listeners, young adult hearing impaired listeners, and older adult hearing impaired listeners. Phrases were presented using varied inter-word intervals and the demand on working memory was altered by the response task, which involved either final word repetition or phrase repetition. The older adult groups performed more poorly than the young groups on low predictability phrases and also on the response task involving working memory, which suggests that the speech understanding difficulties experienced by some older adults may be influenced by age-related memory decline.

One of the major challenges when researching the effects of cognitive decline is to isolate non-auditory factors from peripheral factors. Humes (2002) attempted to overcome this issue in a study which involved fitting participants with identical hearing aids; therefore restoring the frequencies of the speech spectrum and reducing the effects of audibility. Both aided and unaided speech recognition scores were measured in a sample of 71 older adults (aged 60 to 89 years). In addition, measures of cognitive function (WAIS-R) and auditory processing (TBAC and three measures from the Veterans Administration Compact Disc for Auditory Perceptual Assessment) were completed. Results showed significant variance in scores, to which the principal contributor was speech audibility measures. However, variance was also explained by correlations with age-related non-verbal IQ and non-age related verbal IQ measures, which suggests that age-related cognitive decline may also influence speech understanding. These results were supported by Humes and Floyd (2005), which involved participants of a similar age, and utilised the same tests of auditory processing and cognitive function. Results indicated that although speech audibility appeared to have the predominant influence on speech understanding, cognitive functioning and age had more influence than audibility on individual differences in performance on the majority of auditory processing measures. However, there was some variance in auditory processing that could not be attributed to any of the variables explored in the study, illustrating the difficulty researchers have isolating the contribution of peripheral, central auditory and cognitive deficits to speech understanding.

In summary, the literature suggests that peripheral, central auditory and cognitive factors may all contribute to some extent to the speech understanding difficulties experienced by older adults with hearing loss. However, a consensus is yet to be reached regarding the relative contributions of each component, as the effects interact and are therefore challenging to isolate.

1.2.4 Considerations Regarding Assessment and Speech Stimuli

It is important to consider the different types of speech stimuli employed when comparing studies that assess speech understanding. For example, studies cited in the preceding review used a range of tasks such as phoneme and spondee perception (van Rooij et al., 1989; van Rooij & Plomp, 1990), closed set nonsense syllable identification tasks (Humes & Christopherson, 1991; Humes & Roberts, 1990), tasks involving final word repetition (Gordon-Salant & Fitzgibbons, 1993), through to sentence repetition (Gordon-Salant & Fitzgibbons, 1997). It is intuitive to expect that sentence materials would pose greater challenges to the speech understanding of older adults compared with those involving phoneme or word identification, as the added linguistic content and increased length require greater contributions from higher cognitive processes such as working memory, which may decline with age. For example, Humes and Christopherson (1991) discussed that the nonsense syllable identification tasks used in their study have a lower cognitive load in comparison to tasks involving more complex stimuli, which may have limited the ability to assess non-auditory factors such as memory and attention. In order to address this issue, some studies examined the difference in performance on a combination of tasks such as open set word recognition, closed set key word repetition and sentence identification measures (Jerger et al., 1991).

Further consideration when selecting speech stimuli needs to be made with regards to linguistic context. The extrinsic factors that enable a listener to extract the meaning of speech include acoustic and linguistic cues, application of learned phonological syntactical rules, interpretation of contextual cues (both auditory and non-auditory) and prediction on the basis of semantic probabilities (Bellis, 2003). Due to the redundancy in spoken language (extrinsic redundancy) as well as redundancy within the auditory system from repeated representations of an auditory signal throughout the central pathways (intrinsic redundancy), listeners with normal hearing and auditory processing abilities are able to understand a degraded or distorted speech signal. This ability is often compromised in listeners with auditory processing deficits, presumably reflecting a reduction of intrinsic redundancy (Bellis, 2003). Therefore, when working with a population for whom intrinsic redundancy may be compromised, careful consideration must be given to the linguistic demands and semantic predictability of the speech materials used. Speech material with higher semantic predictability may be easier to understand than material with lower semantic predictability, even when all other factors are held constant. These factors must be considered in research design as the characteristics of stimuli may significantly affect the results of speech understanding tasks, depending on the difficulty.

1.2.5 The Effects of Reduced Speaker Intelligibility

As previously discussed, there is evidence to suggest that older adults with hearing loss have more difficulty understanding speech than younger listeners with equivalent hearing loss when the signal has been experimentally degraded. It could therefore be expected that other causes of degradations of the speech signal, such as a reduced ability of a natural speaker to produce intelligible speech, would also have an effect on speech understanding abilities. Techniques typically used in the literature to degrade the speech signal experimentally include the use of reverberation or time compression of a signal (Divenyi et al., 2005; Gordon-Salant & Fitzgibbons, 1993). However, there is a paucity of research utilising speech stimuli that is *naturally* less intelligible, such as speech stimuli collected from speakers with speech disorders, those who have foreign accents, or speech that is naturally characteristic of older adult speakers. The production of normal speech is dependent on the interaction of the processes of respiration, phonation, sensation, resonance and articulation. Age-related changes may occur in any or all of these processes (Sonies, Stone & Shawker, 1984) resulting in negative effects upon the clarity or intelligibility of the acoustic signal. The effects of age upon speech production are detailed below. These effects are particularly important when considering that the main communication partners of older adults with hearing loss are likely to be older adults themselves; therefore difficulties understanding naturally degraded speech will result in a significant impact on overall communication ability. In general, studies have examined age-related changes in two areas: oral motor function and voice characteristics. These changes will be discussed in the following sections.

1.2.5.1 Oral Motor Function

In general, studies that have examined oral motor function have reported that changes occur within the speech mechanism with increased age; causing decreased speed and precision of articulation. Baum and Bodner (1983), in their investigation of oral motor function in healthy participants aged 23 to 88 years, reported that age-related declines were observed in lip posture, masticatory muscle function, and tongue function. Such declines may result in an increased possibility of speech impairment for older individuals (Baum & Bodner, 1983). Changes to the speed of articulatory movement with ageing have also been reported. Parnell and Amerman (1987) used oral diadochokinetic tasks (fast repetition of the syllables ‘pa’, ‘ta’ and ‘ka’) to determine whether ageing or pathology resulted in changes to the speed of articulator movement. Young normal speakers (aged 21 – 28 years), older normal speakers (aged 67 - 81 years) and dysarthric speakers completed the study tasks. Significant differences were found between the age groups for overall rate of syllable production, precision of articulation, loudness control and voice quality. Similar findings of reduced speed of articulatory movement were obtained by Padovani, Gielow and Behlau (2009) in their study of 23 young adults and 23 older participants. In addition, the older adult group exhibited increased loudness variation than the younger group, with these differences attributed to subtle age-related changes in the laryngeal mechanism (Padovani et al., 2009). Overall, the above studies illustrate that age-related changes occur to both the articulatory and laryngeal mechanisms.

1.2.5.2 Voice Quality

Greater research attention has been focused on the effects of ageing upon voice characteristics. Perceptual studies have reported that, in general, ageing voices are perceived as breathy, hoarse, unstable and different in pitch compared to younger voices (Gorham-Rowan & Laures-Gore, 2006). Ptacek, Sander, Maloney and Jackson (1966) reported that the characteristics on which listeners identify older speakers are phrasing, hesitancy, voice breaks, and vitality. Furthermore, Ryan and Burk (1974) determined that the five characteristics of speech that were most highly correlated with judgements of age were voice tremor, laryngeal tension, air loss, imprecise consonants and slow articulation rate. It was also suggested that the speech of normal older adults could be considered to have mild dysarthric qualities, which is a form of motor speech disorder resulting from neurological impairment, for which there is a continuum of the extent of impairment (Ryan et al., 1974).

These perceptual findings are supported by acoustic analyses of the voices of older adults. Age-related changes in the acoustic parameters of fundamental frequency, amplitude variations and perturbation measures have been reported (Ferrand, 2002; Xue & Deliyski, 2001; Xue & Hao, 2003). With regards to fundamental frequency (F0), when the results of older males and females are combined, the group tends to exhibit significantly lower F0 compared to young or middle aged adults (Xue & Deliyski, 2001). However, when each sex is compared separately, the average F0 of females tends to drop with increasing age (Ferrand, 2002), whereas the average F0 of older males tends to rise (Boone & McFarlane, 2000). Xue and Hao (2003) investigated the physical reasons for these age-related differences in acoustic parameters and found that the length and volume of the oral cavity increased in older adults (both male and female) in comparison to younger participants, which resulted in perceptual changes such as the lowering of formant frequencies (particularly F1) across vowels.

Age-related changes to other acoustic parameters of voicing have also been observed. Older adults demonstrate significantly higher frequency and amplitude variations and greater noise levels (as measured by noise-to-harmonics ratio) than younger participants (Xue et al., 2001). These results were supported by Ferrand (2002) in an examination of the harmonics-to-noise ratio, jitter and F0 of young adult females (21 to 34 years), middle-aged females (40 to 63 years) and older adult females (70 to 90 years). Overall, the harmonics-to-noise ratio was significantly lower in the older adult group as per Xue et al. (2001), indicating that there was more noise (possibly from turbulent airflow during phonation) in the signal. However, no significant differences were found between the three groups with regards to jitter, which led the author to conclude that this is a less sensitive measure of vocal instability than harmonics-to-noise ratio (Ferrand, 2002).

Age-related changes have also been observed in the interaction of multiple components of speech production. Ptacek et al. (1966) reviewed the differences in respiratory, phonatory and articulatory processes between younger adults (under 40 years) and older adults (over 65 years). Reduced pitch range was observed in the older group, which was attributed to age-related calcification and weaker muscles within the larynx. Age-related reductions in maximum vowel intensity, maximum vowel duration, maximum intraoral breath pressure and vital capacity were also observed, which suggests loss of power of the respiratory and laryngeal muscles. Decreased diadochokinetic rate was also apparent, which supports the findings presented above (Padovani et al., 2009). Interestingly, there were no significant changes in the laryngeal mechanism on examination (Ptacek et al., 1966). Furthermore, Gorham-Rowe and Laures-Gore (2006) examined the relationship between the perception of certain age-related voice characteristics (breathiness and hoarseness) and a number of acoustic variables (such as F0 standard deviation, amplitude perturbation quotient and harmonics-to-noise ratio) in both young and older adults. Acoustic measures revealed increased variation in F0, noise-to-harmonic ratio and amplitude perturbation quotients in the older group, which suggests that the amount of noise in the voice increases as a function of age. In addition, significant correlations were found between these acoustic results and the perceptual features of breathiness and hoarseness.

As identified above, the process of ageing may affect a wide variety of speech and voicing parameters including, but not limited to, speech rate, vocal pitch, loudness and quality. However, as with other age-related changes, there is much individual variation with regards to the rate and extent of the effect (Mueller, 2007). It has been suggested that the extent of change within the laryngeal mechanism relates to the overall physical condition of the individual, which can change at variable rates. Acoustic features that reflect laryngeal function (such as F0, phonation range, jitter and shimmer) have been investigated using participants from three age groups (25 to 35 years, 45 to 55 years and 65 to 75 years) who were divided into two levels of physical condition (good and poor). This was assessed using indicators such as blood pressure, percentage fat and resting heart rate. It was found that those in poor physical condition had more shimmer, jitter and smaller phonation ranges than those from the same age group in good physical condition. Interestingly, there were no significant effects of age or physical condition on measures of F0, which suggests that the changes that occur within the larynx are usually subtle (Ramig & Ringel, 1983).

The findings presented above suggest that there are a range of speech characteristics affected by the process of ageing. These effects combine to result in a degraded acoustic signal, which may increase the speech understanding difficulties that older adult people with hearing loss tend to experience.

1.2.5.3 Listener Effort

In addition to the speech mechanism itself, recent research attention has focused on the role of the listener in speech intelligibility. One component of intelligibility highly relevant to individuals with hearing loss is that of listener effort; specifically how much effort is required on the part of the listener to understand the speaker. Whitehill and Wong (2006) aimed to determine which relevant perceptual speech features primarily contributed to judgements of effort. Twenty young healthy listeners were required to undertake three tasks – orthographically transcribe sentences from speakers with dysarthria, provide ratings of listener effort (using a 10 cm visual analogue scale from "no effort required" on the left to "maximum effort required" on the right), and select (from a list) the relevant perceptual features they felt contributed to perceptions of listener effort for that speaker. Results showed a strong negative correlation between sentence intelligibility scores and listener effort ratings, as well as moderate to strong correlations between listener effort and articulation errors, and slurred speech. In addition, suprasegmental features such as voice quality were a significant predictor of effort ratings. It is reasonable to suggest, on the basis of these findings, that the naturally degraded speech signal of older adults may also require increased effort on behalf of the listener in order to correctly perceive the message. As yet, this has not been considered as a factor in studies of speech understanding for older listeners.

Listener effort has, however, been considered with regards to hearing impaired individuals and amplification. Signal processing strategies such as noise reduction (NR) have been employed for hearing aids in noisy situations in order to increase speech intelligibility and ease of listening for hearing aid users. Although there appears to be a lack of benefit with regards to speech intelligibility (Hickson, 1994), clinical experience has shown subjective reports from hearing aid users; suggesting that they perceive improved sound quality and ease of listening using NR. These observations have been qualified in a recent study by Sarampalis, Kalluri, Edwards and Hafter (2009) which investigated whether NR technology reduces the cognitive load required for extracting speech in noise. Two dual task experiments were completed by 25 young normal hearing adults. The first experiment involved listening to sentences (both high and low predictability) in quiet and in babble (with sentences at -2 or 2 dB signal-to-noise ratio (SNR)). In babble, the sentences were either unprocessed or processed using an NR algorithm. Accuracy of key word recognition was assessed and participants were also asked to remember the words for later recall. Experiment two also involved repeating sentences in quiet and in babble (at -6, -2 or 2 dB SNR), both with and without NR processing. A simultaneous visual reaction time task was also undertaken to assess speed of processing. The results of both experiments showed that although NR did not improve speech intelligibility in noise (in fact, in experiment one this was significantly better without NR) it appeared to improve recall of high predictability words and speed of processing during the visual task, particularly at the lowest SNR. This suggests that in the most challenging listening situations, the use of NR may result in less listener effort; therefore allowing cognitive resources that would normally be required to extract the speech from the noise to be allocated to other tasks. Although the above study involved normal hearing participants, it has been proposed that because of the degraded auditory input experienced by listeners with hearing impairment, they may need to rely more on cognitive resources to complete processes such as auditory closure than those with normal hearing (Rabbitt, 1991).

In summary, the range of speech characteristics affected by the process of ageing may combine to result in a degraded acoustic signal. It is possible that this may increase the speech understanding difficulties that older adults with hearing loss tend to experience, as well as resulting in an increased amount of required effort to correctly perceive the signal. The increase in effort required may result in more cognitive resources being allocated to the decoding of the speech signal rather than being allocated to other cognitive processes such as working memory and the extraction of meaning (Samparalis et al., 2009). As the main communication partners of older adults may themselves be older adults, the combined factors of reduced speaker intelligibility and hearing impairments of the listener have implications for the audiological assessment and treatment of the older adult population.

1.3 Statement of the Problem

Previous literature has reported that older adult listeners, particularly those with hearing loss, have increased difficulty understanding speech in situations in which the signal is degraded (Divenyi et al., 2005; Gordon-Salant & Fitzgibbons, 1993). To date, significant research efforts have been devoted to determining the major contributing factors to these difficulties, particularly in regards to age-related peripheral, central auditory and cognitive deficits (Gordon-Salant & Fitzgibbons, 1997; Humes, 1996, 2002; Humes & Christopherson, 1991; Humes & Floyd, 2005; Humes & Roberts, 1990; Jerger et al., 1989). However, a consensus has not yet been reached. To date, the majority of such literature has focused on laboratory-based experiments in which the acoustic signal is degraded using techniques such as time compression or reverberation. It is important to consider how these difficulties may impact the listener's overall communication ability in everyday listening conditions.

It has been noted that there are many features of speech in older adult individuals that may deteriorate and represent a degraded acoustic signal (Baum & Bodner, 1983; Ferrand, 2002; Padovani et al., 2009; Ramig & Ringel, 1983; Xue & Hao, 2003). As the primary communicative partners of older adult hearing impaired individuals tend to be older adults themselves, deficits in the listener's ability to understand naturally degraded speech will compound the overall difficulties in communication. As previously suggested, 'typical' older adult speech can be considered to be on the mild end of the dysarthric continuum (Ryan & Burk, 1974), so it is possible that hearing impaired listeners may have more difficulty understanding the speech of normal older adults in comparison to younger adults with normal speech.

To date, research has not examined the speech understanding abilities of older adults using speech stimuli from older adult speakers. Listener-related aspects of intelligibility, such as listener effort, may also play a role in speech understanding. Particularly for hearing impaired listeners, increased reliance on cognitive resources to understand speech may be required than those with normal hearing due to the intrinsically degraded auditory signal (Rabbitt, 1991; Rakerd, Seitz & Whearty, 1996); therefore the process of listening itself requires more effort. There is currently a paucity of information regarding the effects of hearing loss on subjective measures of listener effort and intelligibility in hearing impaired individuals.

1.3.1 Aims of the Study

This study aims to answer three specific research questions. These are as follows:

1. Does the speech understanding ability of older adults with SNHL vary as a factor of speaker age (young versus older) and stimulus predictability (high versus low)?

2. Is there a significant difference in the listener effort ratings of older adults with SNHL when listening to speech from young versus older speakers, and across low versus high predictability phrases?
3. Are the percentage word intelligibility scores of older adults with SNHL, under the above conditions, correlated with tests of central auditory processing?

1.3.2 Hypotheses

It was hypothesized that the speech understanding abilities (as measured by percentage words correct scores) of the listeners with SNHL will: (1) significantly decrease when speech stimuli are presented from the older adult speaker group compared to the young adult speaker group, and (2) significantly decrease when the stimulus consists of low predictability phrases in comparison to high predictability phrases. It was also hypothesised that increased listener effort would be required when attempting to understand the speech from the older adult speaker group, and the low predictability phrases. Furthermore, it was hypothesized that the speech understanding scores of the older adults with SNHL will be correlated with measures of central auditory processing.

Chapter 2. Method

2.1 Listener Participants

Participants included 19 individuals (10 males and nine females) with age-related SNHL, aged between 60 and 87 years (mean age of 71.4 years, SD= 8.48 years). All were native speakers of New Zealand English. Participants were recruited from the client database at the University of Canterbury Speech and Hearing Clinic. SNHL was determined using behavioural pure tone audiometry. Assessment of the severity of the hearing loss was made by calculating the PTA of thresholds at 500, 1000, 2000 and 4000 Hz. A PTA of 20 dBHL or worse in the better hearing ear was required for participation, which represents at least a mild to moderate high frequency hearing loss. Although a range of hearing loss severities were exhibited across participants, the pattern of sloping high frequency hearing loss appears consistent and is characteristic of age-related hearing loss (Gates & Mills, 2005). Hearing losses were also required to be symmetrical, with PTA interaural differences of no greater than 19 dB at any frequency (Jerger et al., 1991). Participants with a hearing loss from childhood, a previous history of neurological disorder, dementia or other significant medical history were excluded from the study. See Figure 1 for the pure-tone air conduction thresholds (combined left and right ear) for each participant. In addition, tympanometry results yielded from each participant were consistent with SNHL (see Appendix II).

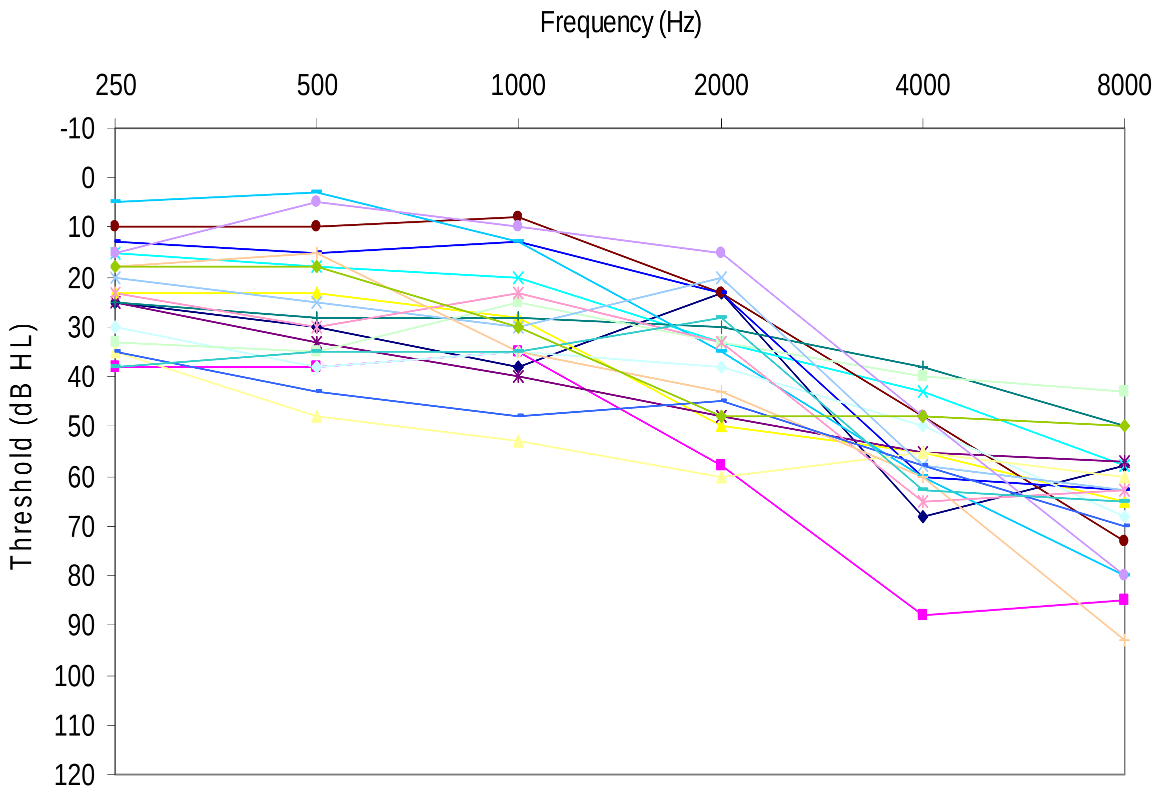

Figure 1. Pure-tone air conduction thresholds (combined left and right ear) for hearing impaired participants.

Ten of the 19 participants were hearing aid owners, with nine owning binaural hearing aids and one having a unilateral hearing aid. However, only five of the participants who had hearing aids wore them on a regular basis. Participants were compensated for their involvement in the project. Approval for this study was obtained from the University of Canterbury Human Ethics Committee. All participants were fully informed of the procedures and signed consent forms prior to participation in the study.

2.2 Speech Stimuli for Listening Experiment

The experimental speech stimuli were recorded from a total of eight speakers (four males and four females) who were recruited from among the friends and colleagues of the researcher. Four speakers (two males and two females) were included in each of the following age groups: (1) 'Young adults' aged 18 – 30 years (mean age 27.13 years), and (2) 'Older adults' adults aged 70 years and above (mean age 80.15). All speaker participants were native speakers of New Zealand English. Seven of the eight speakers were from the South Island and none had a strong regional accent. All speakers were free of colds or other respiratory issues that may have affected their speech at the time of the recording. In addition, they had no history or presentation of neurological disorder, speech or language disorder, or uncorrected hearing loss.

Speech samples were collected during a single one hour session with each speaker. Each speaker provided two minutes of spontaneous speech, read a short passage of connected speech (The Rainbow Passage) and read lists of short phrases which made up the experimental stimuli. The experimental stimuli were comprised of two sets: (1) low inter-word predictability, which were chosen in order to lessen semantic and linguistic cues that might assist in speech understanding (Liss, Spitzer, Caviness, Adler & Edwards, 1998, 2000), and (2) high inter-word predictability, adapted from the Speech in Noise (SPIN) Test (Kalikow, Stevens, & Elliot, 1997). Both sets consisted of 72 phrases, and where necessary the phrases were modified to include six syllables each (see Tables 1 and 2 for examples of the experimental phrases used, and Appendix I for a full phrase list).

Table 1. Examples of experimental phrases – low inter-word predictability (Liss et al., 1998, 2000).

Mark a single ladder	Account for who could knock
Cheap control in paper	Divide across retreat
Its harmful note abounds	Done with finest handle
Hold a page of fortune	Attend the trend success
Narrow seated member	For coke a great defeat

Table 2. Examples of experimental phrases – high inter-word predictability (adapted from Kalikow et al., 1997).

Original Phrase (Kalikow et al., 1997)	***Experimental Phrases as Used***
All the flowers were in bloom	The flowers were in bloom
We saw a flock of wild geese	We saw a flock of geese
I cut my finger with a knife	Cut the bread with a knife
The little girl cuddled her doll	The girl cuddled her doll
The soup was served in a bowl	Soup is served in a bowl

Digital audio recordings of the speech samples were made in a quiet room using a Dell Latitude D630 laptop. An Audix HT2 Headset Condenser Microphone with an Audix APS-911 Condenser Pre-amplifier was connected to an M-Audio Fast Track Guitar/Microphone Recording Interface, which was in turn connected to the laptop. Recording levels were monitored to avoid peak clipping. Sony Sound Forge Version 9.0a (Madison Media Software Inc, 2007) was used to record samples, and a sampling rate of 48 kHz with 16 bits of quantisation was employed. For all speakers the microphone was placed approximately six centimetres from the mouth during recordings. Speakers were given time to familiarise themselves with the speech stimuli prior to commencement of the recording. If hesitations or reading errors occurred during the recording, the speaker was asked to repeat that element. The speakers were given rest times throughout the recording as necessary. Once the speech stimuli were recorded, those who participated in this part of the study were no longer required. All speaker participants were compensated for their involvement.

Following recording, the experimental phrases were edited using Sound Forge to eliminate microphone noise and to insert one second of silence prior to and following each phrase. The amplitudes of the samples were normalised to an RMS level of -18.5 dB (re: 0 dB full scale). An equal-loudness contour was used for the level calculation, and parts of the file with an amplitude less than -50 dB (calculated with an attack/release time of 200 ms) were ignored. As there were 72 phrases in each list, a total of 36 low predictability phrases and 36 high predictability phrases were used from each group in the final experimental stimuli set (with nine spoken by each speaker). The phrases from each speaker were examined by the principal investigator and the nine phrases deemed most representative of each speaker's age were selected for use.

2.2.1 Acoustic Analysis

Acoustic analysis was completed on all of the 144 experimental phrases included in the listening experiment. All acoustic measures were completed using TF32 analysis software (Milenkovic, 2001). Measures were carried out using an amplitude-by-time display of the waveforms, with settings of 7.020 frequency range, a floor of -78 dB and LPC selected. The beginning and end points of each phrase were selected by placing cursors on the first and last evidence of phonemes on the spectrographic display. Analysis was completed for each speaker and data were combined to calculate mean values for each speaker group. Analysis consisted of the following measures:

1. *Variation in fundamental frequency (Hz)*: F0 and the variation within each phrase were computed using the pitch trace. All pitch traces were inspected visually to identify apparent anomalies which were removed before analysis.
2. *Variation in amplitude (dB)*: The RMS amplitude of each phrase was automatically converted to mean decibels with the standard deviation across the phrase employed for analysis.
3. *Speech rate:* The start and finishing points of each phrase were selected, which gave the initial and final time in milliseconds. Calculations were then made to determine the

number of syllables spoken per second.

4. *First and second formant of selected vowels:* The START, FLEECE and THOUGHT vowels were selected for analysis as they form the modern New Zealand English vowel space (Maclagan, 2009). An equal number of vowels from each group, balanced between male and female, were analysed. Measures of the first and second formants were taken from the temporal midpoints of each vowel using both spectrograms and LPC displays.
5. *Measures of voice quality*: The THOUGHT vowel was used for analysis of voice quality, as this was the most frequency occurring and was evenly distributed between speakers. Twelve occurrences of the THOUGHT vowel were analysed from each group, with equal numbers from males and females. A static portion based around the temporal midpoint of the vowel was selected, and measures of percentage jitter, percentage shimmer and SNR were calculated.

Differences on the above parameters between speaker groups were evaluated using t-tests. Results are presented in Table 3.

Table 3. Mean, standard deviation and t-test results of acoustic parameters for young versus older speakers.

		Young Speakers	**Older Speakers**	**Significance**
Variation in pitch (Hz)		27.50 (12.57)	33.69 (15.67)	$t_{(136)}$ = -261, P<0.01
Variation in amplitude (dB)		12.49 (2.29)	12.44 (2.81)	$t_{(142)}$ = 0.10, p=0.92
Speech rate (syllables/sec)		4.11 (0.55)	3.02 (0.55)	$t_{(142)}$ = 11.90, p<0.01
% Jitter		2.75 (2.65)	1.25 (1.31)	$t_{(16)}$ = 1.75, p=0.1
% Shimmer		13.53 (12.08)	8.53 (13.86)	$t_{(22)}$ = 1.75, p=0.36
Signal-to-noise ratio		12.6 (6.59)	18.63 (6.33)	$t_{(22)}$ = 1.75, p<0.05
START	*F1*	803.33 (113.90)	829.33 (150.07)	$t_{(9)}$ = -0.31, p=0.76
	F2	1513 (176.12)	1448 (126.55)	$t_{(9)}$ = 0.67, p=0.52
FLEECE	*F1*	318.17 (40.77)	360.5 (54.56)	$t_{(9)}$ = -1.39, p=0.2
	F2	2302.33 (364.94)	2282.5 (264.42)	$t_{(9)}$ = 0.1, p=0.92
THOUGHT	*F1*	441.36 (54.37)	461.5 (65.0)	$t_{(14)}$ = -0.63, p=0.54
	F2	818.75 (109.30)	898.5 (168.48	$t_{(14)}$ = -1.05, p=0.31

Note: Standard deviation values are presented in parenthesis

Analysis revealed no significant differences with regards to variation in amplitude, percentage jitter, percentage shimmer or F1 and F2 of the THOUGHT, START and FLEECE vowels. However, there were significant differences in F0, with the young speaker group presenting with less variation in pitch than the older speaker group. The difference in speech rate was also significant, with the older group presenting with a slower rate of articulation. SNR is a measure of voice perturbation that calculates the energy ratio between the harmonic components and the noise components within the vowel that was measured. The older group demonstrated a higher SNR, indicating that for the THOUGHT vowel this group had less voice perturbation, which may result in a vowel sound that is perceived to be more clear (Milenkovic, 1987).

Re-analysis was completed on 20% of the acoustic data set of the experimental stimuli (12 phrases) for reliability purposes. This included 10% of the high predictability phrases and 10% of the low predictability phrases. To determine intra-rater reliability, the investigator who conducted the initial measurements also completed the second set of reliability measures. Pearson's product moment correlations were conducted to test the reliability between the first and second measurement sets, and the absolute between-measure difference was also calculated. Analysis indicated that reliability was found to be acceptable. The data are presented in Table 4.

Table 4. Intra-rater reliability measures of acoustic parameters.

Parameter		**Absolute Difference**	**Pearson's Correlation**
Variation in pitch (Hz)		2.75	r = 0.989
Variation in amplitude (dB SD)		0.42	r = 0.985
Speech rate (syllables/sec)		1.20	r = 0.942
% Jitter		0.49	r = 0.728
% Shimmer		1.89	r = 0.439
Signal-to-noise ratio		0.87	r = 0.978
Vowels	*F1 (Hz)*	11.08	r = 0.997
	F2 (Hz)	34.43	r = 0.998

To determine inter-rater reliability, an investigator not involved in the original measurements completed the second set of reliability measures. Pearson's product moment correlations were conducted to test the reliability between the first and second measurement sets. The data are presented in Table 5. Again, analysis indicated that reliability was found to be acceptable.

Table 5. Inter-rater reliability measures of acoustic parameters.

Parameter		Absolute Difference	Pearson's Correlation
Variation in pitch (Hz)		2.37	r = 0.991
Variation in amplitude (dB SD)		0.35	r = 0.984
Speech rate (syllables/sec)		0.09	r = 0.986
% Jitter		0.34	r = 0.869
% Shimmer		1.61	r = 0.608
Signal-to-noise ratio		0.63	r = 0.984
Vowels	*F1 (Hz)*	11.33	r = 0.995
	F2 (Hz)	37.33	r = 0.998

2.3 Procedures

Prior to commencement of the study, listener participants completed the Mini-Mental State Examination (MMSE) (Folstein, Folstein & McHugh, 1975). This was undertaken to exclude any participants with the co-occurrence of significant cognitive involvement. All participants passed the MMSE. They then underwent several standard audiological assessments to confirm their suitability for participation, which included otoscopy, pure tone audiometry (air conduction and bone conduction) and tympanometry. Pure tone audiometry was not repeated on those participants who had been tested within six months prior to their participation. Pure tone audiometry was carried out using a Grason-Stadler GSI 61Audiometer using ER-3A insert earphones (or Telephonics TDH-SDP supra-aural headphones if inserts were contraindicated). Tympanometry was carried out using a Grason-Stadler GSI TympStar. In accordance with clinical protocols, all equipment used during testing had been calibrated on a yearly basis. The listening experiments were carried out in a sound treated room at the University of Canterbury Speech and Hearing Clinic.

Once initial assessment results confirmed eligibility for the study, each participant completed two experimental components: (1) the speech understanding and listener effort tasks, and (2) assessments of central auditory processing. These tasks were counterbalanced to minimise order effects. A total of two and a half hours was required for participation. This took place over one or two sessions, depending on individual preference. Rest periods were built into the session as deemed necessary. Hearing aid wearers were not permitted to wear their hearing aids during the listening experiments or tests of central auditory processing.

2.3.1 Listening Experiment

The experimental phrase presentation and response recording was completed using the University of Canterbury Perceptual Speech Ratings (UC-PSR) computer programme (O'Beirne, 2009), which was specifically designed for speech perception research. For the experiment, participants were seated in front of a laptop. Those who had not had previous experience with computers were given brief instructions on how to operate the mouse. The researcher operated the mouse on the behalf of those participants who were not comfortable to do so. The experimental phrases were presented through Sennheiser HD280 Pro circum-aural headphones. Prior to commencement of the experiment, a speech sample from a speaker who was not included in the final stimuli set was presented, and the participants were instructed to use the on-screen sliding scale to adjust the volume until it was at a comfortable listening level (see Figure 2). No further volume adjustments were allowed after this point.

Figure 2. Screen print of the volume selection screen used during the speech understanding task.

The participants were advised that they would hear some short phrases, which were spoken by both males and females of different ages. The phrases were presented one at a time and the participant controlled the rate of presentation, as the next phrase was not presented until they clicked the "next" button. In addition they were told, in lay terms, that some of the phrases contained high context, and some of the phrases contained low context and would therefore not necessarily be semantically correct. They were instructed to listen to each phrase and repeat it exactly as they heard it. The order of phrase presentation was randomly generated for each participant and repetition of phrases was not permitted. Listeners were encouraged to give their best attempt if they were unsure of the complete phrase. Following each attempt the researcher typed their response into the computer, giving participants the chance to confirm that the transcription was accurate. This procedure was used because the majority of participants had indicated that they would not be comfortable typing their own responses as they were not familiar with computers. After stating what they heard for each phrase, participants were further instructed to rate how much effort was required to recognise each phrase using a computer-based listener effort scale. A 10 cm visual analogue scale was presented on the screen, and participants were required to point the mouse to a location on a continuum, from "minimal effort" to "maximum effort" (see Figure 3). Effort ratings were recorded on the basis of the distance (in centimetres) from the left end of the scale to the marked point.

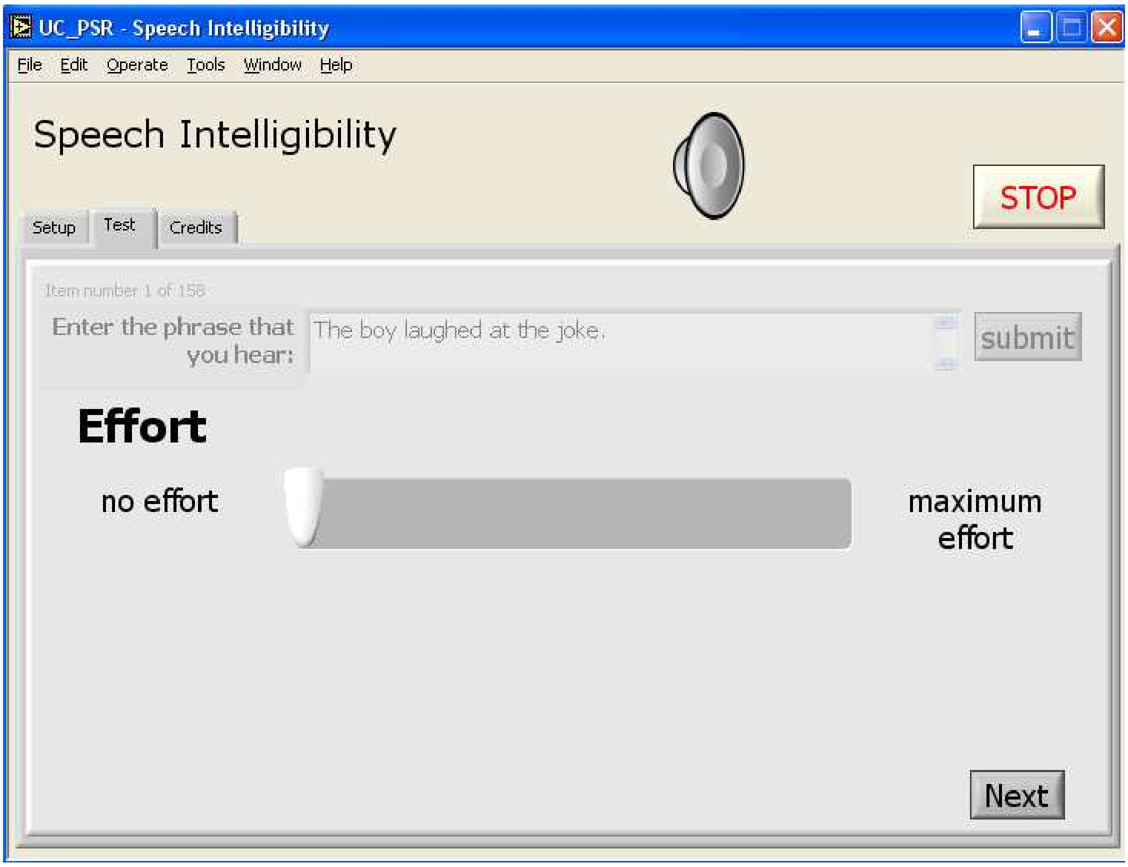

Figure 3. Screen print of the listener effort scale used during the speech understanding task.

On completion of the task, the data from UC-PSR was exported to a Microsoft Excel spread sheet for analysis. Each phrase transcription was then scored on the basis of the percentage of words correct. In order for a word to be considered correct, it had to be recorded exactly (for example, addition or deletion of a plural /s/ was scored as incorrect, and homophones were scored as correct).

2.3.1.1 Measurement Reliability

To assess the reliability of responses to the experimental stimuli during the listening experiment, 20% of all phrases (10% of the low predictability and 10% of the high predictability phrases) were presented twice during the listening experiment. Pearson's product moment correlations were conducted to test the reliability between the first and second set of measures with regards to percentage words correct and listener effort. The correlation between the first and second set of measures for percentage words correct was 0.725, with an average absolute between-measure difference of 4.54%. The correlation between the first and second set of measures for listener effort was 0.998, with an average absolute between-measure difference of 0.698.

2.3.2 Central Auditory Processing Assessments

Three standardised tests of central auditory processing were conducted. All three are tests typically performed within a clinical assessment battery for CAPD, and are thought to be relatively resistant to peripheral hearing loss. Details of the tests are provided below.

1. Dichotic Digits Test (DDT) (Musiek, 1983): This test is comprised of two parts: (1) The Single Pairs subtest, and (2) The Double Pairs subtests. The Single Pairs subtest consists of 50 pairs of digits from one to nine (excluding seven) with one digit from each pair being presented to each ear simultaneously. This subtest was used as a practice task; therefore twenty of the items were completed by each participant. The Double Pairs subtest consists of 100 pairs of digits from one to nine (excluding seven)

with four digits being presented during each trial (two in each ear simultaneously). Participants were instructed that they would hear numbers from one to nine in each ear at the same time, and to repeat all the numbers that they heard for each presentation. When they were unsure, they were encouraged to guess. A score was obtained by taking the percentage of digits correct in each ear. Scores of 90% and above were considered to be within the normal range (Museik, 1983). The results from the Double Pairs subtest only were used for analysis, as this is a more complex task.

2. Staggered Spondaic Words Test (SSW) (Katz, 1968): This test consists of 40 pairs of spondees, and each ear receives one spondee which partially overlaps in time with the spondee presented to the other ear. Participants were instructed that they would hear two words in each ear at the same time, and that the words would overlap. They were then required to repeat back both words that were heard. The SSW yields scores for four listening conditions presented during the test; right non-competing, right competing, left competing and left non-competing. Full scoring of the SSW as intended by the authors (Katz, 1968) involves obtaining the Raw SSW Score (R-SSW), which is the percentage of errors in each of the four conditions, and providing a correction factor to convert to a C-SSW score. From this score, categories of dysfunction (relating to those proposed by Katz and colleagues referred to as the Buffalo Model) can be assigned (for example, ranging from normal to severely abnormal) from which inferences can be made regarding site of dysfunction. However, the Buffalo Model is a theoretical construct, and, like other theoretical models of CAPD, is not universally accepted (Bellis, 2003). In addition, normative information is only available for individuals aged up to 69 years, which is not applicable to the majority of participants involved in the current study. Furthermore, the analysis involves correcting for the hearing loss by taking into account scores on

PB Words lists, which were not available for each participant in this study; therefore full scoring was not possible. Bellis (2003) stated that the SSW can be scored in the same manner as other dichotic tests, therefore the present study analysed the results in terms of the R-SSW scores, which gives the percentage error in each listening condition. When assessing auditory processing the conditions of most interest are the left and right competing conditions, as these involve binaural integration. Therefore, in comparing R-SSW scores to scores on the DDT and speech recognition scores, the competing condition which yielded the *worse* score for each participant was selected to make this comparison.

The DDT and the SSW are both tests of dichotic separation, however they were both used in the current investigation as they involve different levels of linguistic loading (Bellis, 2003) and both tests are widely used in clinical settings.

3. Random Gap Detection Test (RGDT) (Keith, 2000): This test was chosen as it assesses temporal processing skills, which is a different aspect of auditory processing than that assessed by the DDT and SSW. The RGDT consists of a series of paired tone pip stimuli containing various inter-stimulus intervals ranging from zero to 40 milliseconds. The first subtest is a practise task, and during the second subtest the stimuli were presented at 500, 1000, 2000 and 4000 Hz. Participants were instructed that they would hear one or two beeps, very close together ("almost like an echo"). They were asked to state whether they perceived one or two beeps. The number of reported beeps was recorded, and the gap detection threshold at each frequency was calculated by determining the interval for which the participant consistently identified two tones. The gap detection threshold at each frequency was then averaged to find

the composite gap detection threshold across frequencies. Gap detection thresholds of less than 20 milliseconds are considered normal and therefore indicate that a listener does not show evidence of a temporal processing disorder.

Tests of central auditory processing were completed using a Grason-Stadler GSI 61 Audiometer and an Onkyo DX-C390 Compact Disc Changer. ER-3A insert earphones were used unless contraindicated, in which case Telephonics TDH-SDP supra-aural headphones were used. All tests were presented through separate channels on the audiometer at a level of 50 dB sensation level (SL) as per instructions, to compensate for each participant's level of hearing loss.

2.3.3 Statistical Analysis

Analysis of Covariance (ANCOVA) was used to determine if significant differences existed in percentage words correct scores as a factor of speaker group (young versus older speakers) and stimulus predictability (high predictability versus low predictability phrases). Given the difference between participants in level of presentation, presentation level (dB) was employed as a covariate. For listener effort, paired t-tests were used to determine if differences existed in the perceived effort for speaker group and stimulus predictability. Pearson's product moment correlations were conducted to determine whether a significant relationship existed between scores on the tests of central auditory processing (DDT, SSW and RDGT) and percentage words correct scores for the low predictability listening condition.

Chapter 3. Results

3.1 Listening Experiment

3.1.1 Speech Understanding Scores

Figure 4 contains the mean percentage words correct scores of the 19 participants with SNHL, presented by speaker age group allocation (i.e., young versus older) and stimulus predictability (high predictability versus low predictability phrases). Individual participant percentage words correct scores for the different conditions are presented in Appendix III.

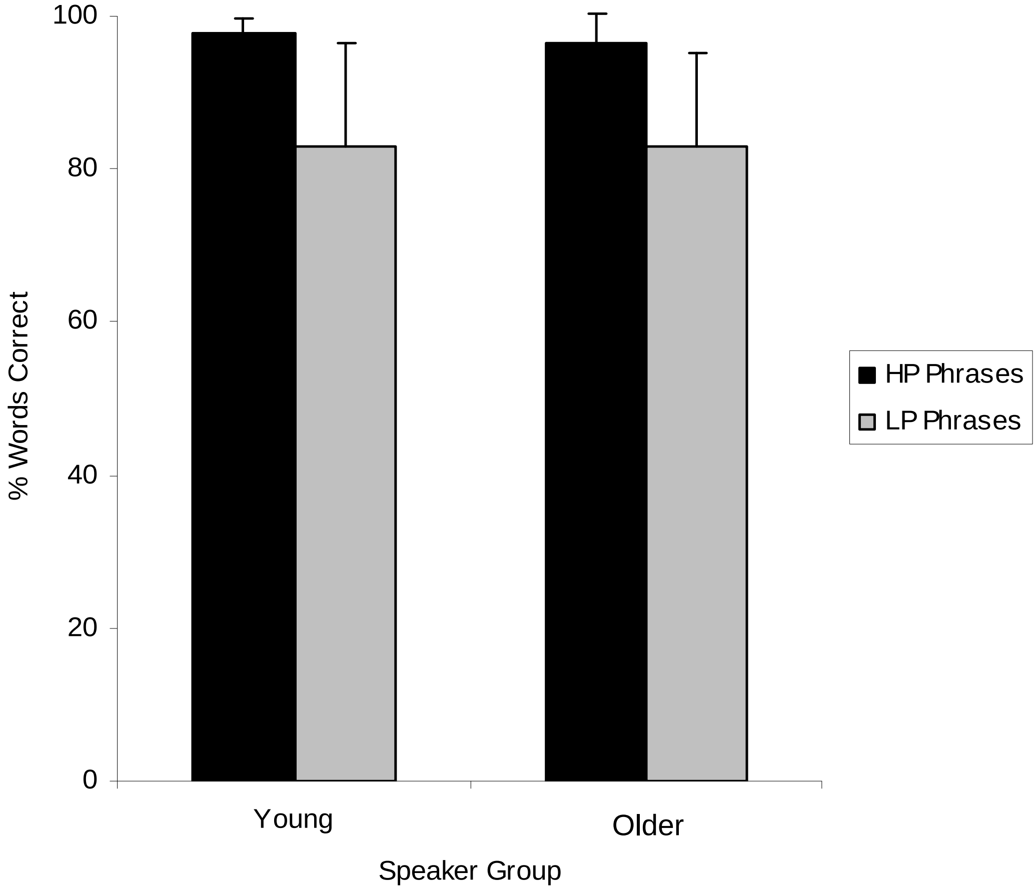

Figure 4. Mean word recognition scores (percentage correct) across speaker group and stimulus predictability.

When controlling for presentation volume as a co-variate, analysis revealed a significant main effect for stimulus predictability (F=43.90, p<0.001), indicating that as expected, percentage words correct scores were significantly higher for high predictability phrases. There was no significant effect of speaker group ($F=0.10$, $p>0.05$), signalling that the participants exhibited a similar level of difficulty understanding the speech of both young and older speakers. Furthermore, the group X stimulus predictability interaction was not significant ($F=0.06$, $p>0.05$).

3.1.2 Listener Effort Ratings

Figure 5 depicts the mean perceived listener effort for the group of 19 participants with SNHL when listening to younger compared to older speakers. Figure 6 shows the mean perceived listener effort for the group with SNHL when listening to low versus high predictability phrases. Statistical analysis revealed that the listener group with SNHL required significantly increased perceived effort when listening to the speech of the older adult group versus the young adult group ($t_{18} = -2.46$, $p<0.05$). Furthermore, significantly increased perceived effort was also evident when listening to low predictability phrases versus high predictability phrases ($t_{18} = -4.33$, $p<0.05$).

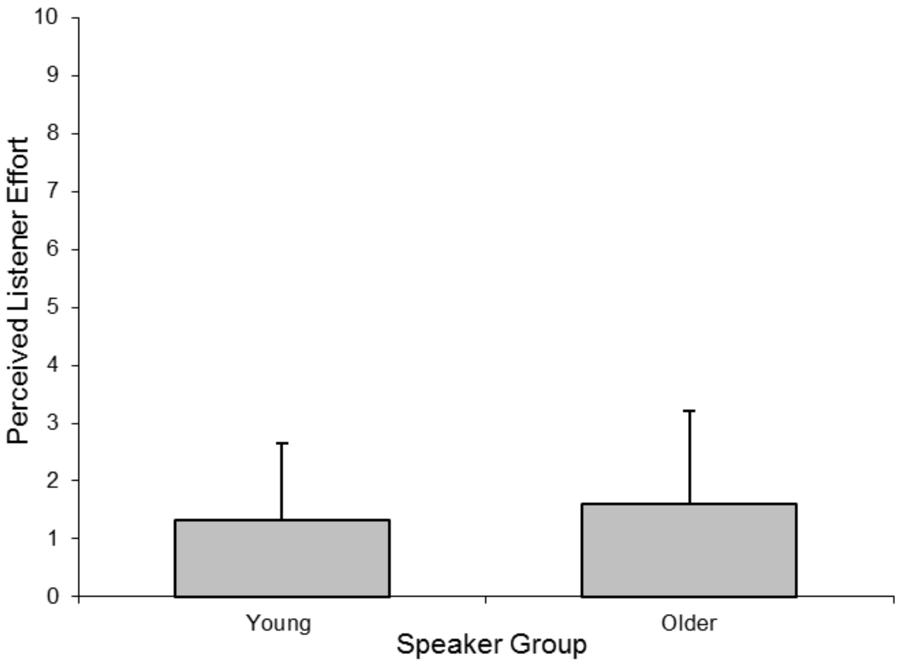

Figure 5. Mean perceived listener effort by speaker group.

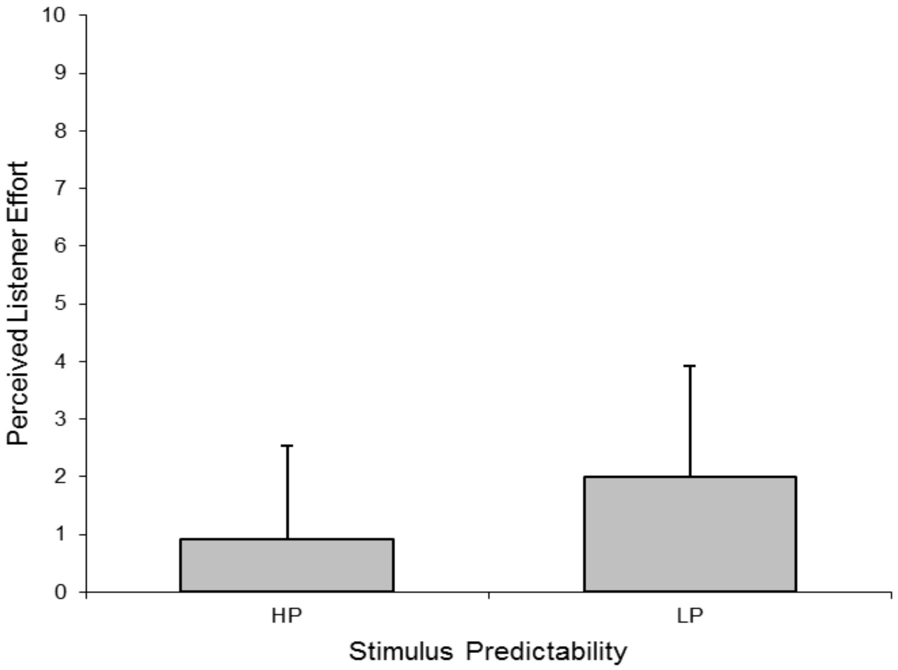

Figure 6. Mean perceived listener effort by stimulus predictability.

3.2 Tests of Central Auditory Processing

For examination of the relationships between tests of auditory processing and percentage words correct scores, individual listener's results on the low predictability stimuli were selected for comparison. The low predictability score for comparison comprised the average of a listener's responses to speech from both younger and older listeners. It was considered acceptable to collapse the data as no significant difference existed in percentage words correct scores for the factor of speaker group (i.e., young versus older speakers). The low predictability results were chosen for comparison as the results from the speech understanding test indicated that performance of the listener group approached ceiling in the high predictability stimulus conditions.

3.2.1 Dichotic Separation

Dichotic Digits Test

Individual scores of the listener participants on the Dichotic Digits Test (DDT) for the Single Pairs and Double Pairs subtests are available in Appendix IV. As stated in the method, results from the Double Pairs test only were selected for analysis. The relationship between DDT score (for both the left and the right ear) and percentage words correct for low predictability phrases is presented in Figure 7. Correlational analysis revealed that a moderate correlation existed between percentage words correct for low predictability phrases and performance on the DDT in both the left ear ($r=-0.631$, $p<0.01$) and the right ear ($r=0.645$, $p<0.01$).

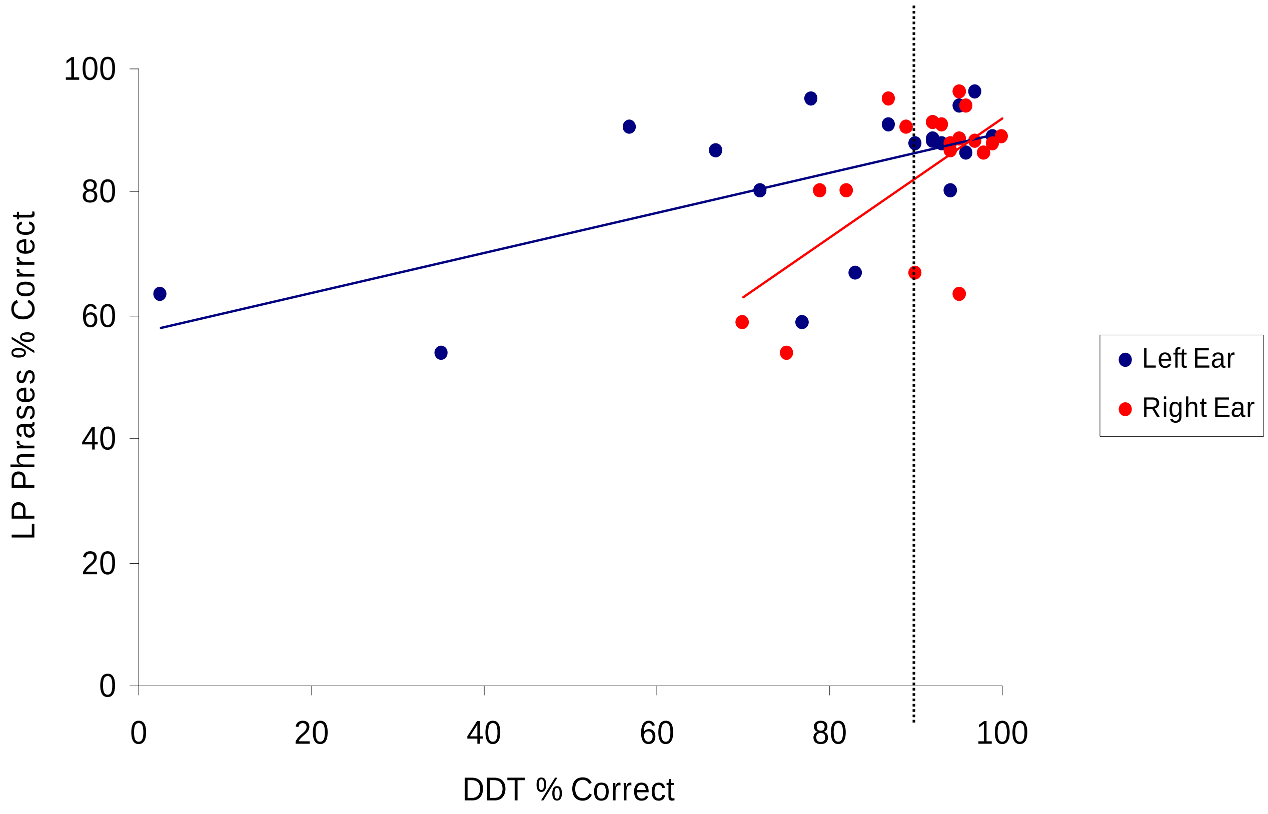

Figure 7. Dichotic Digits Test Double Pairs scores for the left and right ears versus speech recognition score for low predictability phrases (dashed line represents the accepted pass criterion used clinically (90%)).

Staggered Spondaic Words Test

The relationship between R-SSW scores (worse competing condition) and speech recognition score for low predictability phrases is presented in Figure 8. Statistical analysis revealed a significant negative correlation between R-SSW score and speech recognition scores for low predictability phrases (r=-0.761, p<001). In addition, individual participant R-SSW scores across listening conditions are available in Appendix V, and the relationship between R-SSW scores (worse competing condition) and scores on the DDT (for the corresponding ear) is presented in Appendix VI.

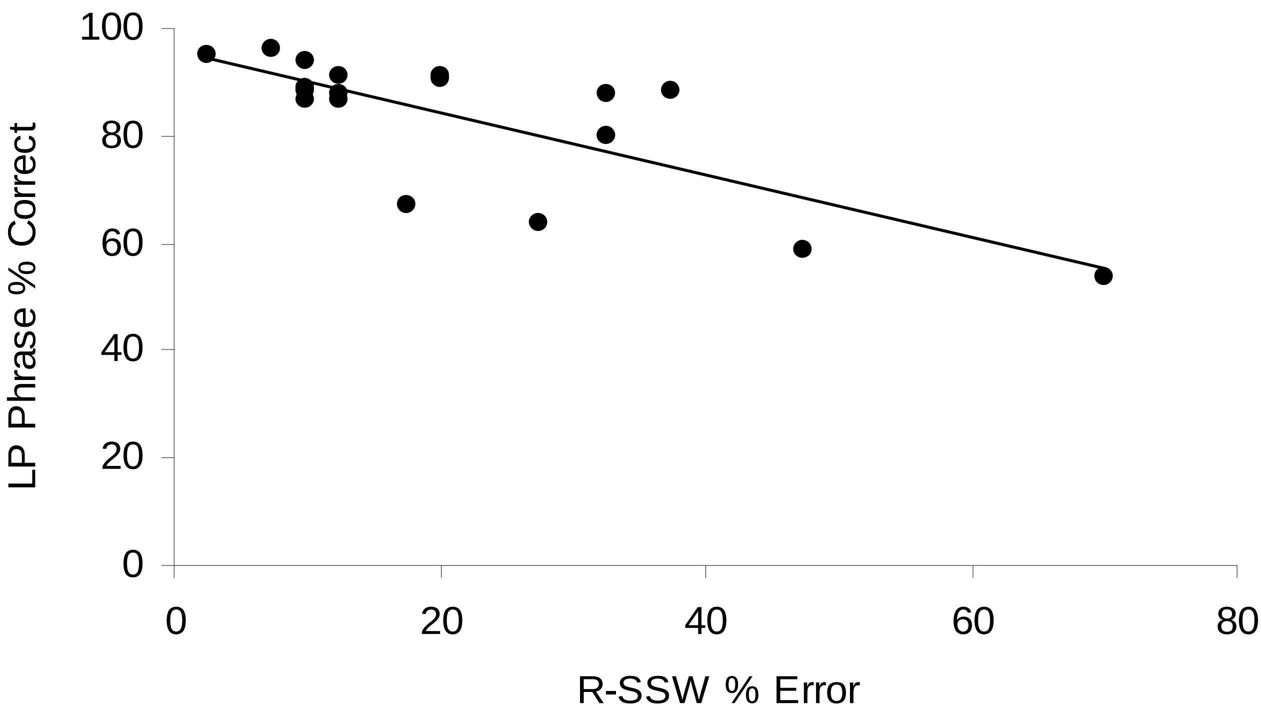

Figure 8. R-SSW scores for the worse competing condition versus speech recognition scores for low predictability phrases

3.2.2 Temporal Processing

Random Gap Detection Test

Figure 9 demonstrates the relationship between average RGD thresholds and percentage word correct scores for the individual listeners with SNHL. Statistical analysis indicated that the correlation between RGD score and speech recognition score for low predictability phrases was not significant (r = -0.31, p=0.203). Gap detection thresholds across the frequency range for each participant are presented in Appendix VII.

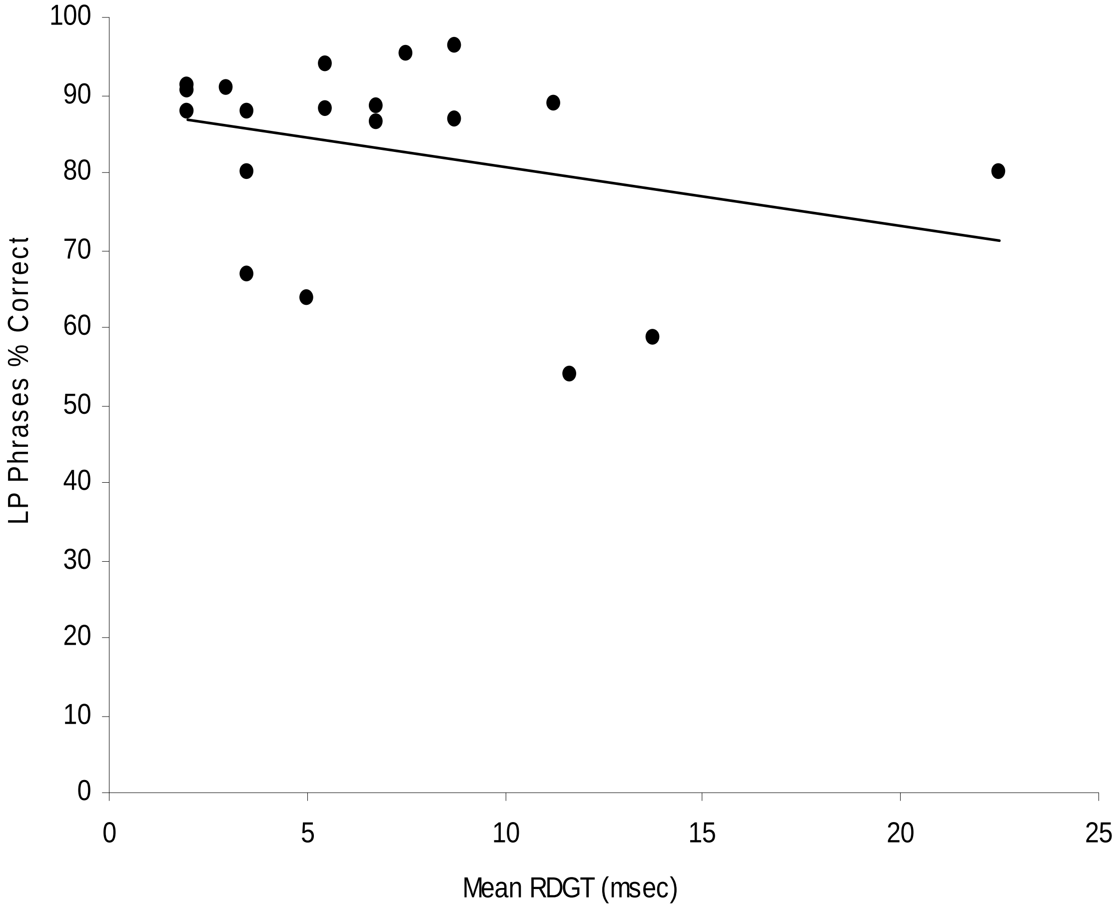

Figure 9. Average Random Gap Detection thresholds versus speech recognition score for low predictability phrases.

Chapter 4. Discussion

The purpose of this study was three-fold. Firstly, the study aimed to determine whether a group of 19 individuals with age-related hearing loss exhibited a significant difference in their ability to understand speech stimuli presented from young adult speakers and older adult speakers, and across two stimulus conditions, low predictability and high predictability phrases. Secondly, the project aimed to establish whether the degree of perceived listener effort varied across these conditions. Finally, the study examined whether individual differences in percentage words correct scores were related to performance on a series of measures of central auditory processing.

We hypothesised that, due to the negative effects of ageing upon speech production, the accuracy with which hearing impaired listeners could understand speech from older individuals would be significantly reduced and increased listener effort would be required when compared to results achieved when listening to the speech of younger individuals. In addition, it was expected that decreased percentage words correct scores and increased listener effort would be observed in the low predictability condition. Furthermore, it was projected that individual differences in speech understanding would be related to performance on measures of central auditory processing.

The primary findings of the study indicated that: (1) the speech understanding ability of older listeners with SNHL was similar when listening to the speech of young versus older speakers, (2) phrases containing low predictability were more difficult to understand than high predictability phrases as they yielded lower speech understanding scores, (3) listeners perceived that greater effort was required to understand the speech of older versus young speakers, and low versus high predictability phrases, and (4) two measures of dichotic separation were correlated with percentage words correct scores. However, no relationship was found between performance on a temporal processing task and percentage words correct scores; indicating that dichotic separation ability may be related to the speech understanding abilities of older adults with SNHL. Each of these primary findings will be discussed in detail below.

4.1 Effects of Speaker Age and Stimulus Predictability

4.1.1 Speaker Age

Results of the current study showed that the speech understanding ability of the listener group with age-related hearing loss did not vary as a factor of age of the speaker. These findings were unexpected as it was hypothesized that speech from the older speaker group would yield significantly lower speech understanding scores than the younger group due to age-related natural degradations in the speech signal. However, the findings are perhaps not surprising due to the minimal acoustic differences observed between the speech samples of the young and older speaker groups. Although significant differences were found between groups with regards to SNR, F0 standard deviation and speaking rate, it appeared that these acoustic differences did not affect the overall signal quality sufficiently to produce differences in speech understanding scores. These results are in contrast with reports of reduced intelligibility with regards to experimental degradations in signal quality (Gordon-Salant & Fitzgibbons, 1993). However, these degradations tend to be far more severe than those which occur naturally through age. In addition, it is difficult to predict the rate and extent to which age affects vocal characteristics as there is significant individual variation (Mueller, 2007), and the extent of general physical decline may be a stronger predictor of age-related changes in the speech and laryngeal mechanisms (Ramig & Ringel, 1983). It is possible that the current speakers chosen to represent “older” speech did not present with the vocal characteristics that are typically associated with the ageing voice.

Another possible explanation for the lack of variation in speech understanding scores between the young and older speaker groups is that the reduced speech rate observed within the older speaker group may have facilitated speech understanding as listeners had more time to process the speech. Increased processing time may have compensated for any degradation to the signal, therefore leading to the similar scores between groups. Overall, the lack of variation in speech understanding scores between the young and older speaker groups in the current study suggest that the age-related changes in speech do not create significantly adverse listening conditions to result in an increase in the speech understanding difficulties experienced by older adults with SNHL.

4.1.2 Stimulus Predictability

Although the speech understanding ability of the group with age-related hearing loss did not vary as a factor of speaker age, variations in speech understanding scores were observed as a factor of stimulus predictability. The results of the current study revealed a decrease in percentage words correct scores for low predictability phrases in comparison to high predictability phrases. The finding of decreased scores for low predictability phrases is not unexpected, and is likely explained by the fact that the context present in the high predictability phrases facilitated speech understanding.

In order for effective communication to occur, the listener utilises a range of processes such as cognition, auditory memory, auditory closure, meta-linguistic strategies and knowledge of grammar, semantics and pragmatics to arrive at the meaning of the utterance (Sweetow & Henderson-Sabes, 2004). There are two main factors which have been proposed to affect speech understanding; acoustic features (such as length and phonetic context) and linguistic factors (such as complexity of the sentence and word familiarity) (Marshall, 1985). In the current study, listeners were able to make use of semantic cues to aid their understanding of the high predictability phrases; whereas, they had more difficulty understanding the low predictability phrases due to the lack of such cues.

The current findings are consistent with the literature which has examined the effects of context on speech understanding. All of the studies discussed below used similar stimuli, based on those developed for the SPIN Test (Kalikow et al., 1977), which also formed the basis for the high predictability phrases in the current study. Firstly, Craig (1988) reported that for normally hearing young adults, key word recognition scores were higher when preceded by high predictability phrases than low predictability and carrier phrases. These results are consistent with those of the current study which suggest that speech understanding is aided by phrase context. Furthermore, in a study involving 30 young and 30 older adults (with hearing within normal limits for their age), Hutchinson (1989) reported that both groups achieved lower key word recognition scores when preceded by low predictability than high predictability or carrier phrases. Interestingly, the older adult group achieved lower key word recognition scores than the younger group regardless of the stimulus predictability. Measurements were also taken at varied signal-to-babble ratios, and further results showed that the older adult group had particular difficulty understanding the speech in the babble conditions, across predictability conditions. As all participants had relatively normal hearing, the differences in scores cannot be attributed to a reduction in peripheral hearing sensitivity. They were therefore explained by the possibility of age-related changes to the central auditory pathways and cognitive processing. In older listeners, the reduced extrinsic redundancy of the signal in babble would combine with the reduced intrinsic redundancy within the central auditory system to cause increased difficulty with word recognition across all stimulus conditions (Hutchinson, 1989). It was concluded that these higher level processes may be more crucial to speech understanding when linguistic context is unavailable (Hutchinson, 1989).

Overall, the results relating to lower speech understanding scores for older adults in low predictability phrases are supported by previous studies (Craig, 1988; Hutchinson, 1989). These findings suggest that it is necessary to take contextual factors into account when developing speech materials, depending on the type of processing strategies that are desired to be elicited.

4.2 Listener Effort

In general, listeners reported little effort for all tasks; however significant differences were found between listening conditions. Firstly, the results of the current study showed that the group of 19 listeners with SNHL perceived that significantly greater levels of effort were required to comprehend the speech of the older speakers. Although the acoustic differences between the speaker groups did not appear to significantly affect speech understanding, it is possible that the acoustic and perceptual differences between the young and older speakers were enough to result in increased perceived listener effort when dealing with older speech. Indeed, perhaps greater attentional resources were required on behalf of the listeners in order to achieve equivalent speech understanding scores between speaker groups. There is a paucity of research regarding the degree of effort that listeners perceive is required in their everyday speech understanding. As previously mentioned, Whitehill and Wong (2006) studied dysarthric speakers and found a correlation between listener effort measures and sentence intelligibility scores. Furthermore, those speakers with slurred speech and articulation errors resulted in listeners reporting increased effort ratings, followed by features relating to voice quality (such as strain-strangled, breathy and harsh voice). It was noted that listening to speech with decreased intelligibility puts more demands on the listener; leading to higher listener effort ratings (Whitehill & Wong, 2006). In addition, the study by Sarampalis et al (2009) suggested that greater cognitive resources need to be allocated to extracting the speech signal in challenging situations such as background noise; resulting in increased listener effort. The current study did not directly investigate the relationship between speech understanding and listener effort. However, the fact that listeners perceived that more effort was required to understand the older speakers suggests that some of the perceptual features that lead to reduced intelligibility may have been present within the sample. This suggests that greater processing resources were required when listening to the older group in order to maintain the same level of intelligibility.

Furthermore, as expected, significantly greater levels of perceived effort were required when the older listeners were presented with low predictability phrases compared with high predictability phrases. This is intuitive to expect, given the finding that low predictability phrases yielded lower percentage words correct scores than high predictability phrases. It is likely that central auditory processes such as auditory closure are more crucial to speech understanding when linguistic context is unavailable (Hutchinson, 1989), therefore resulting in increased cognitive resources being allocated to the process; accounting for the higher listener effort scores observed for low predictability phrases.

Overall, results regarding listener effort ratings suggest that although age-related degradations in signal quality between the speaker groups were not significant enough to reach the critical threshold to affect intelligibility, increased listener effort was required to maintain the same level of speech understanding as with speech from the younger group. This may be explained in part by the presence of age-related perceptual characteristics that have been proposed to increase the necessary effort for speech understanding (Whitehill & Wong, 2006). In addition, results suggest that speech without linguistic context is perceived as more difficult to understand than speech containing such context. Further research is needed to extend the current understanding of listener effort, particularly in relation to older listeners in everyday listening situations.

4.3 Relationship between Speech Understanding and Central Auditory Processing

Two tests of dichotic separation (DDT and SSW) and one test of temporal processing (RGDT) were used to assess the auditory processing skills of the older adults with hearing loss. The results were compared to those from the speech understanding task to determine whether a relationship existed between these aspects of central auditory processing and speech understanding ability.

4.3.1 Tests of Dichotic Separation

The current study involved two tests of dichotic separation: the DDT and the SSW, which were used as a gauge of the participants' central auditory processing skills. Results revealed a moderate positive correlation between scores on the DDT (for both left and right ears) and percentage words correct scores for low predictability phrases, indicating that those who achieved better percentage words correct scores also scored more highly on this measure of central auditory processing. In addition, a significant negative correlation was found between R-SSW percentage error scores (worse competing condition) and percentage words correct scores for low predictability phrases, indicating that those who achieved higher speech understanding scores made fewer errors on the SSW. It is also interesting to note that the results revealed a negative correlation between R-SSW scores (worse competing condition) and scores on the DDT (for the corresponding ear) (see Appendix VI), which is to be expected as both are standard assessments of the same process, albeit containing different levels of linguistic loading. These results are consistent with the hypothesis that individual differences in speech understanding would be related to performance on measures of central auditory processing.

Analysis of the individual results of the DDT and SSW is necessary in order to determine whether there is any evidence of CAPD among the participants. The standard pass criterion for the DDT is 90% (Museik, 1983). Results from the test show that five out of the 19 participants scored below the pass criterion in both ears, indicating difficulties with dichotic separation. This difficulty may be observed behaviourally as a problem hearing speech in background noise, or when more than one person is speaking simultaneously (Bellis, 2003). Further analysis can be completed with regards to the right ear advantage, which relates to the fact that normal hearing right-handed individuals achieve consistently higher scores on dichotic tasks in the right ear than the left ear when the task is linguistically loaded (Kimura, 1961). This occurs due to the decussating nature of the auditory pathway, as signals from the right ear are sent directly to the language dominant cortical hemisphere (usually the left); whereas input to the left ear must cross from the right hemisphere to the left via the corpus callosum. Therefore, the right ear advantage (REA) is considered a measure of interhemispheric processing (Bellis, 2003). Five participants from the current study demonstrated a significant REA (above 10% difference), 10 demonstrated a slight REA (1-9%), and three demonstrated slightly higher scores in the left ear. Only one participant achieved exactly the same score in both ears. An extreme example of an REA was yielded from Participant 17, who achieved a pass score of 95% in the right ear and a score of 2.5% in the left ear. In this instance, investigations took place during testing to ensure the results were not due to faulty equipment setup or user error. However, this was not the case. The participant could complete the task when digits were presented monaurally to the left ear, but showed great difficulty during the dichotic task. The participant is a regular user of hearing aids which have been fitted binaurally. No factors were mentioned during the case interview that can account for these results; therefore suggesting that this participant has significant difficulty with dichotic separation. This participant also demonstrated lower than average performance on the speech understanding tasks across stimulus predictability conditions, but particularly with the low predictability stimuli, which is consistent with expectations.

With regards to the individual results of the SSW (see Appendix V for full details) it is difficult to compare the results to those of other studies, which used the traditional scoring methods as in Katz (1968). However, the R-SSW percentage error scores can be evaluated qualitatively, by reviewing the pattern of results from each condition (right non-competing, right competing, left competing and left non-competing). Three main patterns of results were evident. Five participants demonstrated decreased performance on both competing conditions, eight participants demonstrated decreased performance on one condition in particular, and five participants achieved relatively even performance across all conditions. Participant 12 yielded an abnormal pattern of results, demonstrating a very high percentage of errors across all conditions and appearing to have particular difficulty in the left non-competing condition. This may be an indication of deprivation effects in the left ear as the participant wears a hearing aid (although not consistently) in his right ear only. Interestingly, this participant also performed below the mean on speech tasks across stimulus predictability conditions, but particularly with the low predictability stimuli (see Appendix III), which is consistent with expectations. In addition, it is again interesting to note the case of Participant 17, as although extremely poor scores were achieved in the left ear on the DDT, scores on the SSW suggest that this participant had slightly more difficulty during the right competing condition. The reason for this apparent inconsistency is unclear.

Analysis of the individual results suggest that there is some evidence of central auditory processing deficits on tests of dichotic listening within the listener participant group of older adults with SNHL. However, it is unclear whether the observed deficit is specific to dichotic listening or whether poor performance on these assessments indicates a general decline in central auditory processing abilities (Bellis, 2003). Therefore, conclusions regarding interhemispheric processing and the function of the corpus callosum cannot be drawn. However, the finding that speech understanding scores for low predictability phrases were related to performance on measures of dichotic listening may be partially explained by a reduction in intrinsic redundancy that occurs in individuals with CAPD. Auditory closure relates to the process of the listener filling in missing or distorted portions of the auditory signal by combining both intrinsic and extrinsic redundancy, and is therefore important for speech perception in challenging situations, such as when context is not available. As previously mentioned, patients with central auditory deficits may struggle with processes such as auditory closure, possibly due to reduced intrinsic redundancy (Bellis, 2003).

The results from the current study are consistent with previous studies that suggest that central auditory processing deficits are evident within the older adult population (Cooper & Gates, 1991; Stach et al., 1990), and that these deficits add to the speech understanding difficulties observed (Humes & Christopherson, 1991; Jerger et al., 1989). In particular, studies have suggested that a decline in dichotic listening ability occurs as a function of age and hearing loss (Jerger, Chmiel, Allen & Wilson, 1994). The variability in REA found among participants from the current study is consistent with the literature, which suggests that although an REA is typically observed in normal hearing listeners, the asymmetry tends to increase as a function of age and hearing loss (Bellis & Wilber, 2001; Roeser, John & Price, 1976). However, it is difficult to make comparisons based on the current results regarding the relationship between speech understanding scores and measures of dichotic listening as traditional scoring methods were not used.

The DDT and SSW, both tests of dichotic separation, were selected for use as they have been shown to be relatively resistant to peripheral hearing loss (Bellis, 2003). These tools were used as a gauge of the participants' central auditory processing skills. Overall, results revealed that there is evidence that some participants have a deficit in central auditory processing. Furthermore, those participants who demonstrated poorer scores on these assessments of dichotic separation also performed more poorly on the speech understanding task in the low predictability stimulus condition. It is unknown whether the results from the assessment tools used indicate a specific deficit in dichotic listening for these participants, or whether this is indicative of a general decline in central auditory function; therefore conclusions cannot be drawn regarding the causation of this relationship. However, these findings support previous research which suggests that central auditory processing skills are particularly important when listening conditions are more challenging due to the lack of contextual cues (Hutchinson, 1989).

4.3.2 Tests of Temporal Processing

The current findings demonstrate no significant relationship between speech understanding scores for low predictability stimuli and the average gap detection threshold as measured by the RGDT. In addition, results showed that only one participant achieved scores outside the RGDT pass criterion of 20 milliseconds across the frequency range (see Appendix VII). These results suggest that there is limited evidence for the existence of a temporal processing disorder in the participant group with age-related hearing loss.

The RGDT assesses gap detection ability, which is a method of measuring temporal resolution (a sub-skill of temporal processing), and has been associated with the listener's ability to process time-related speech characteristics such as voicing manner and syllable transition (DeFillippo & Snell, 1986). An individual who performs poorly on the RGDT would likely have greatest difficulty perceiving rapidly presented speech (Stach, 2000). The current findings are consistent with previous studies that suggest that gap detection ability does not significantly decrease with age. Moore, Peters and Glasberg (1992) examined the influence of hearing loss on gap detection by comparing gap detection thresholds (GDTs) of 15 older adults with hearing impairment (mean age = 76.3 years) and 11 older adults with near-normal thresholds (mean age = 75.9 years). Results were also compared to previously collected data from young normally hearing participants. It was reported that most of the older adults with near-normal hearing had GDTs within the normal range, which is consistent with the current study and suggests that temporal resolution problems do not always occur with ageing. In addition, the finding that speech understanding scores were not correlated with GDTs is consistent with results from Strouse, Ashmead, Ohde and Grantham (1998), which involved normally hearing younger and older adults (matched for gender and hearing sensitivity). Tests included monaural gap detection, interaural time difference thresholds, and two tests of speech perception. The older group demonstrated increased GDTs and interaural time difference thresholds and also performed more poorly on both speech perception measures. However, no correlation was found between the speech tasks and psychoacoustic measures of temporal processing.

In contrast, there is research evidence to suggest that temporal processing deficits become more evident from the fifth decade of life (McCroskey & Kasten, 1982) and increase as a function of advancing age (Konkle, Beasley & Bess, 1977). Increased GDTs and greater variability have been found in studies examining young and older adults (Schneider, Pichora-Fuller, Kowalchuk & Lamb, 1994; Snell, 1997); therefore suggesting an influence of age on gap detection abilities. Furthermore, Snell (1997) reported that older adults demonstrated increased GDTs in both quiet and noisy conditions, which was thought to reflect a more general decline in the speed of auditory processing. The difference in findings with regards to the current study may be due to differences in methodology, as the validity of the RGDT for identifying CAPD is unknown (Bellis, 2003).

Overall, the literature suggests that temporal processing ability may decline as a function of age, and that there are factors other than peripheral hearing sensitivity that contribute to the temporal processing deficits observed in some older listeners. The results from the current study did not reveal temporal resolution deficits in the majority of participants, or a relationship between speech understanding scores and GDTs. Care should be taken not to draw assumptions on the absolute temporal processing skills of the participants of the current study, as this assessment tool targets only one aspect of temporal processing. Although the sensitivity of other measures such as temporal integration, ordering and brief tone tasks have been shown, further investigation is needed to ensure that commercial versions are available for clinical use (Bellis, 2003).

4.4 Clinical Implications

The results of the current study have implications with regards to audiological assessment and rehabilitation of older adults. Results suggest that central auditory processing skills are related to the speech understanding ability of older adults. Hearing aid fittings are currently based on results from peripheral testing only (i.e. pure tone audiometry), which provides useful information on the degree and type of hearing loss and the level of required amplification. However, clinical observations have shown that there is much variation in the experienced benefit of older hearing aid users, despite similar audiograms (Gatehouse, 1991; Sweetow & Henderson-Sabes, 2006). It may therefore be necessary to consider including tests of auditory processing in the standard assessment battery for this population, as they are currently not routinely assessed. However, there are issues surrounding the implementation of such assessment as there remains contention regarding the lack of a standard definition of CAPD, and the confounding influence of peripheral hearing loss on performance and interpretation of assessment tools. In addition, there are particular difficulties around CAPD testing in older adults as there is often a lack of age appropriate normative information. It has been suggested that using similar tasks in another modality, such as the visual modality, may be the most effective way to distinguish between a CAPD and a general cognitive problem within this population (Humes, 2008). Although this has, in theory, been recognised as a potential way forward in establishing an appropriate test battery (Cacace & McFarland, 2005), steps have not been taken to put this into everyday practice. Further research is therefore needed before a CAPD approach can be considered for clinical use with older adults.

The current findings also suggest that listening conditions such as stimulus predictability may influence the speech understanding ability of older adults. This extends on previous research which suggests that older adults have particular difficulty understanding speech in challenging conditions such as background noise (Divenyi, et al., 2005). Furthermore, this study has shown that higher levels of perceived listener effort are required when listening in more demanding situations (such as increased speaker age and low predictability phrases). Although speech tests, such as the AB Words List (Boothroyd & Nittrouer, 1988) are sometimes utilised in the clinical assessment battery for older adults, these tests require recognition of monosyllabic words in quiet conditions only; therefore do not reflect 'real-world' listening situations. The SPIN Test (Kalikow et al., 1977) is a possible alternative assessment tool as it includes both low predictability and high predictability stimuli, and utilises varying levels of multi-talker babble in order to simulate everyday listening conditions. Although this test has been used extensively in research, there is limited information on its clinical utility (Elliot, 1995), particularly for the older age groups due to a lack of normative information (Hutchinson, 1989). The development of a speech test involving a New Zealand English speaker, phrase or sentence material and a variety of listening conditions (e.g. quiet and background noise) may provide more accurate information regarding the speech understanding abilities of older adults with hearing loss in this country and therefore be more helpful with regards to predicting the likelihood that they will become successful hearing aid users.

With regards to audiological rehabilitation, the current finding that central auditory processing deficits are related to scores on speech understanding tasks has implications for the successful use of hearing aids, which is currently the standard treatment for age-related hearing loss. Although many older adults experience considerable benefit from amplification, some older adults do not achieve successful outcomes regarding improved speech understanding following a hearing aid fitting (Hickson & Worrell, 2003). In particular, it has been acknowledged in previous research that simply restoring audibility through amplification is less effective in people with central auditory processing difficulties (Humes, 2002). This perceived lack of benefit may lead to older adults choosing not to wear hearing aids, which was highlighted in Gates et al. (1990). Findings from a sample of 482 hearing impaired participants (aged 63 to 95 years) showed that only 10.3% completed a hearing aid trial. Furthermore, 22% of those who completed a trial stopped wearing the hearing aids (Gates et al., 1990). Suggested explanations for this lack of satisfaction within the older population include factors such as the cost, stigma of being identified as hearing impaired, aesthetic concerns, fear of the technology and a physical lack of dexterity causing difficulties manipulating hearing aids (Plath, 1991). However, perhaps the most likely reason for dissatisfaction is that hearing aids do not always give users the ability to communicate effectively, especially in listening situations that are not ideal such as in background noise (Vesterager & Salomon, 1991). In addition, difficulty listening in background noise is a common symptom of CAPD (Bellis, 2003).

However, despite the evidence that CAPD may result in less benefit from hearing aids, these skills are not typically addressed in the rehabilitation process for older adults. Perhaps it is necessary to offer alternative treatment strategies for age-related hearing loss that take central auditory function into account, such as auditory training approaches. Approaches involving both bottom-up and top down processes have been shown to cause changes in the auditory system that help older adults recognise temporal differences which may improve their speech understanding (Tremblay, Pikosz & Souza, 2002). An example of a currently available auditory training programme for which there is an increasing research base is the Listening and Auditory Communication Enhancement (LACE) programme (Sweetow & Henderson-Sabes, 2004), which is an interactive software-based program that can be utilised both in the clinic and in the home. Initial outcomes studies on the LACE programme involving sixty-five participants demonstrated significant improvements in all training tasks as well as on all but one post test assessment measure (Sweetow & Henderson-Sabes, 2006). Furthermore, Martin (2007) provided evidence that those who participated in the LACE programme were four time less likely to return their hearing aids than those who did not.

In summary, the findings of the current study advocate for the inclusion of central auditory processing assessments and rehabilitation techniques in a clinical setting in order to ensure the best possible outcomes with regards to the speech understanding abilities of older adults with hearing loss.

4.5 Limitations and Directions for Future Research

The present study has limitations that must be identified when interpreting the results. Attempts to overcome these limitations provide several possibilities that may be explored for future research. Firstly, a wide age criteria was employed with regards to the listener group. Age-related decline in hearing is exacerbated with increasing age; therefore some of the variation in results could be attributed to the wide age range of listener participants being grouped together (60 to 87 years). Other studies that were able to draw participants from larger groups have addressed this by further separating participants into age groups such as ‘young old’ (65 to 75 years) and ‘old old’ (76 to 85 years) (Humes & Christopherson, 1991). In addition, although it would have been preferable to exclude participants who had a history of noise exposure or were experienced hearing aid users, this was not possible in the current study. It was therefore difficult to control for the effects that noise exposure may have had on hearing loss configuration, and that hearing aid use may have had on the individual's auditory system. Future studies could address these issues when defining criteria for participant selection.

Secondly, there were limitations relating to the design of the computer-based listening experiment. Due to the age of the participants, many had limited experience with computers and were not comfortable to type their responses. The task was modified to allow participants to repeat the sentence orally while an examiner provided orthographic transcriptions. As the transcriptions were carried out by one individual, the reliability is unknown. The participants were encouraged to check each transcription before proceeding but this was at times hampered by poor vision and auditory memory deficits. Furthermore, although the listener effort rating component did not necessitate typing, participants were required to use the mouse to enter their effort ratings following each phrase. The task had to be modified in the case of three participants who had no previous experience using a mouse, so they could use their hand to point to the desired location on the screen. This required more time and may have led to limitations in the accuracy of the effort ratings. An additional limitation of the effort rating task was that the starting point of the slider was at "no effort" on the scale for each trial (see Figure 3), rather than having a random starting point. This may have biased participants towards giving low effort ratings. It is recommended that future studies utilise an alternative to a computer-based task for this age group.

Thirdly, the lack of significant differences in the majority of acoustic features between speaker groups may be explained by limitations relating to the age range of the older group (70 to 84 years). Considering the acoustic analysis prior to phrase allocation could have ensured a more even distribution of the desired tokens and may have provided more acoustic contrasts in the sample. In addition, more acoustic differences may be evident between the younger and older speaker groups if the age criteria of the older group was 85 years and older.

Furthermore, it may be interesting to use participants from the other end of the scale, as clinical experience has shown that hearing impaired adults have increased difficulty understanding the speech of children. Acoustically this may be explained by variations in F0 which relates to the thickness and length of the vocal folds. For example, both girls and boys around 6 years of age have similar F0s of approximately 285-295 Hz, which is considerably higher than the average F0s of young adults, which are approximately 125 Hz in males and 220 Hz in females (Boone & McFarlane, 2000). Young children may also have other speech and language features that contribute to this difficulty, such as phonological processes and vocabulary differences.

Lastly, the current study was limited with regards to the assessment of factors other than peripheral hearing sensitivity. The range of CAPD assessment tools was limited to those that were available at the University of Canterbury Speech and Hearing Clinic. In addition, time constraints limited the number of CAPD assessments that could be completed. In particular, it would have been desirable for each participant to complete a standard AB Words List test as well as a speech in noise test in order to ensure that information was gathered on a broad range of auditory processing skills. It may also have been useful to assess another aspect of temporal processing, to improve the sensitivity of the assessment battery. Furthermore, in order to continue investigations on the relative contributions of peripheral and central-auditory processing factors to speech understanding ability, studies should consider making between-group comparisons of the speech understanding skills of older adults with hearing loss to young adults with normal hearing, and young adults with equivalent hearing loss (or with hearing loss that is simulated through the use of spectrally shaped masking noise). This technique has been used previously (Humes & Roberts, 1990; Humes & Christopherson, 1991) in order to gain a better understanding of the speech understanding difficulties of older adults. In addition, the current study did not incorporate measures of cognitive ability such as speed of processing and working memory, which have been suggested to contribute to the speech understanding difficulties of older adults (van Rooij et al., 1989, 1990). A general age-related decline in working memory may contribute to the increased effort required when listening to speech containing low redundancy, and also may affect performance on central auditory tasks involving stimulus recall, such as the DDT. Further information on the relative contribution of cognitive factors could be gained with the inclusion of measures of working memory.

4.6 Conclusions

This study evaluated the speech understanding performance of older adults with SNHL on a computerised speech understanding task (consisting of both low predictability and high predictability phrases spoken by young and older adult New Zealand English speakers). Performance was determined on the basis of percentage words correct scores and the perceived effort required for speech understanding with regards to speaker age and stimulus predictability. In addition, measures of central auditory processing were employed to investigate individual differences in speech understanding performance and the relative contribution of central auditory processing skills. As hypothesized, it was found that the low predictability phrases yielded lower speech understanding scores and required more effort to perceive than high predictability phrases. In addition, a relationship was found between speech understanding scores on the low predictability phrases and tests of dichotic separation (DDT and SSW) but not on the test of temporal processing (RGDT), suggesting that those who performed poorly on speech understanding tasks may demonstrate deficits in some areas of central auditory processing. However, it was found that although speech from the older adult group required more effort to perceive than the young adult group, speech understanding scores between the groups were similar, which is in contrast to the hypothesis and may be due to the similar acoustic features that were present in both samples. This study has provided evidence for the use of CAPD tests and rehabilitative techniques in a clinical setting.

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Appendix I

Experimental phrase list – low inter-word predictability (Liss et al., 1998, 2000).

Account for who could knock
Address her meeting time
Admit the gear beyond
Advance but sat appeal
Afraid beneath demand
Amend estate approach
And spoke behind her sin
Appear to wait then turn
Assume to catch control
Attack became concerned
Attend the trend success
Avoid or beat command
Award his drain away
Balance clamp and bottle
Beside a sunken bat
Bolder ground from justice
Bush is chosen after
Butcher in the middle
Career despite research
Cheap control in paper
Commit such used advice
Confused but roared again
Connect the beer device
Constant willing walker
Cool the jar in private
Darker painted baskets
Define respect instead
Distant leaking basement
Divide across retreat
Done with finest handle
Had eaten junk and train
Embark or take her sheet
For coke a great defeat
Forget the joke below
Frame her seed to answer
Functions aim his acid
Its harmful note abounds
Hold a page of fortune
Increase a grade sedate
Indeed a tax ascent
Kick a tad above them
Listen final station
Mark a single ladder
Mate denotes a judgement
Mistake delight for heat
Mode campaign for budget
Model sad and local
Narrow seated member
Her owners arm the phone
Pain can follow agents
Perceive sustained supplies
Pick a chain for action
Pooling pill or cattle
Push her equal culture
Rampant boasting captain
Remove and name for stake
Resting older earring
Rocking modern poster
Rode the lamp for teasing
Round and bad for carpet
Rowing farther matters
Seat for locking runners
Secure but least apart
Signal breakfast pilot
Sinking rather tundra
Or spent sincere aside
Stable wrist and load it
Submit his cash report
Support with dock and cheer
Target keeping season
Technique but sent result
Thinking for the hearing

Experimental phrase list – high inter-word predictability (adapted from Kalikow et al., 1977).

The flowers were in bloom	The landlord raised the rent	They moved to a new house
We saw a flock of geese	Pour me a cup of tea	Pick a bunch of flowers
Drop the coin through the slot	Wash the floor with a mop	He answered the question
The airplane dropped a bomb	We camped out in our tent	In winter time it snows
The fruit was shipped in crates	Wipe your feet on the mat	The pilot flies the plane
The train ran off the track	The shepherd watched his sheep	The princess wore a crown
The girl cuddled her doll	The scarf was made of silk	Lock the door with a key
Harry fell down the stairs	The host welcomed the guests	He turned down the offer
Soup is served in a bowl	Raise the flag up the pole	The gambler lost the bet
The sailor swabbed the deck	The bride wore a white gown	Fill the car with petrol
Let’s invite the whole gang	The witness took an oath	The workers dig a ditch
The sport shirt had short sleeves	The nurse gave him first aid	Stir your tea with a spoon
The storm broke the boat’s mast	Kill the bugs with this spray	The nest is in the tree
He got drunk in the bar	She took the bus to school	She wrapped up the present
Get the bread and butter	The rose bush has sharp thorns	They waited in the queue
Playing cards can be fun	She felt hot and bothered	The poor man was in debt
The car drove off the cliff	Cut the meat with a knife	The farmer milked the cow
The bees swarmed round the hive	Turn on the radio	She got out of the car
His boss made him work hard	Drive the car down the road	He lent me some money
The fire burned down the house	The dog begged for a bone	The man wrote a letter
The hen laid some brown eggs	Go to sleep on the bed	The student read the book
The girl brushed her long hair	The fish swam down the stream	The ship left on a cruise
The boy licked the ice cream	The burglar went to jail	Pour water down the drain
Wash your hands with the soap	The boy laughed at the joke	She baked a birthday cake

Appendix II

Tympanometry results.

Participant	Right Ear	Left Ear
1	Type A	Type A
2	CNT*	CNT*
3	Type A	Type A
4	Type A	Type A
5	Type Ad	Type A
6	Type A	Type A
7	Type A	Type A
8	Type Ad	Type Ad
9	Type A	Type A
10	Type As	Type A
11	Type A	Type A
12	Type A	Type A
13	Type A	Type A
14	Type A	Type A
15	Type Ad	Type A
16	CNT*	CNT*
17	Type A	Type A
18	Type A	Type A
19	Type A	Type A

Note: CNT* = Could not test due to inadequate seal

Appendix III

Individual participant percentage words correct scores for older speaker (OS) versus younger speaker (YS) group, and high (HP) versus low predictability (LP) phrases.

Participant	% Correct HP Phrases	% Correct LP Phrases	% Correct YS	% Correct OS
1	99.25	91.26	98.22	93.64
2	93.47	58.74	76.63	81.21
3	99.25	86.36	94.38	93.35
4	98.99	96.15	97.93	97.69
5	98.24	80.07	90.53	90.75
6	97.99	88.81	94.67	93.64
7	97.74	94.06	96.15	96.24
8	98.99	90.56	94.67	96.24
9	97.99	88.46	94.97	93.06
10	96.23	66.78	86.69	89.88
11	98.74	95.1	96.15	98.27
12	89.45	53.85	76.92	72.25
13	98.24	90.91	94.97	95.38
14	99.25	88.11	94.97	94.22
15	96.98	86.71	92.6	92.77
16	95.98	80.07	88.76	89.88
17	93.47	63.29	83.43	78.32
18	98.24	87.76	95.27	92.49
19	97.49	87.76	93.2	93.64

Appendix IV

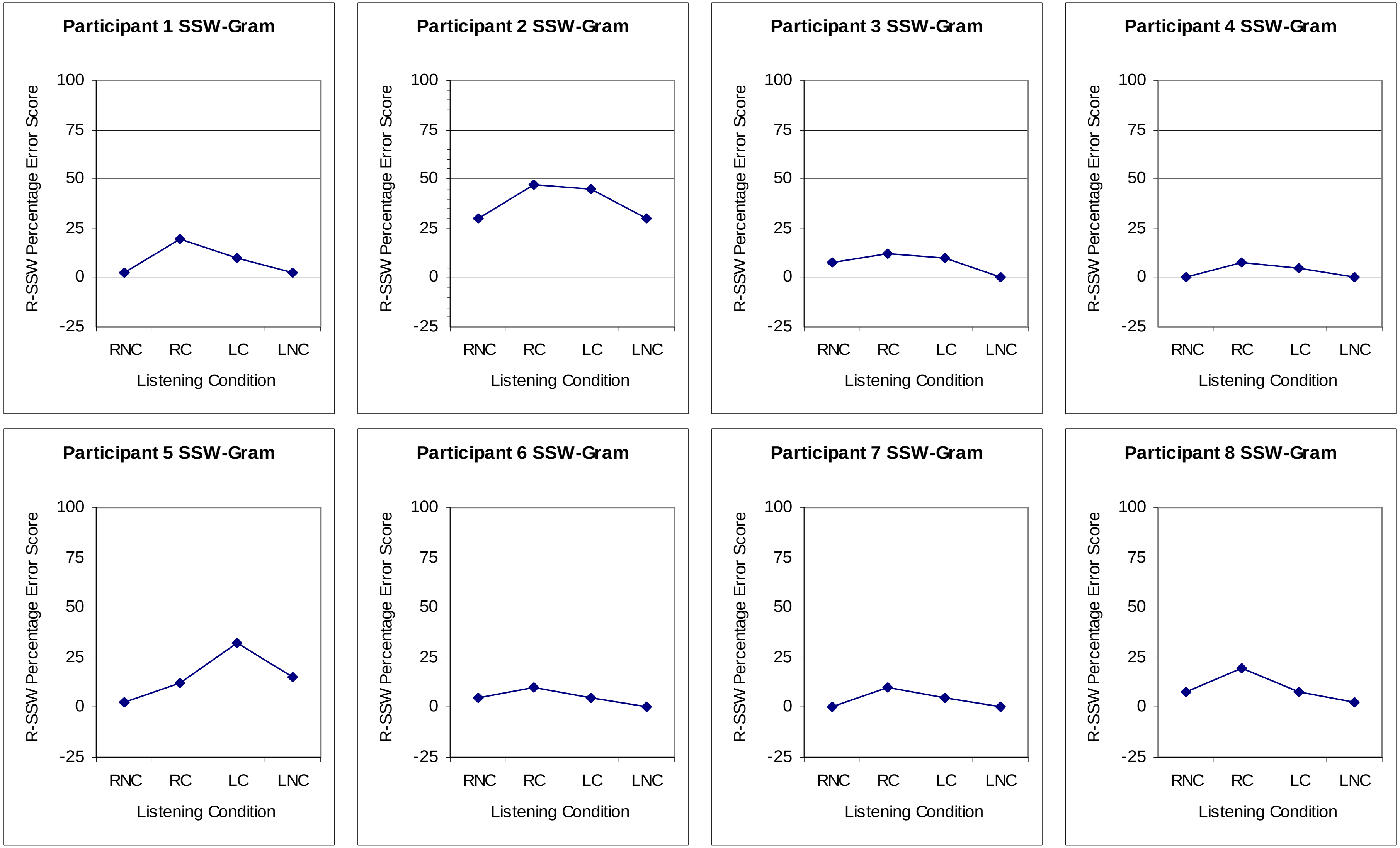
Individual participant scores on Dichotic Digits Test (percentage correct) and measures of the right ear advantage.

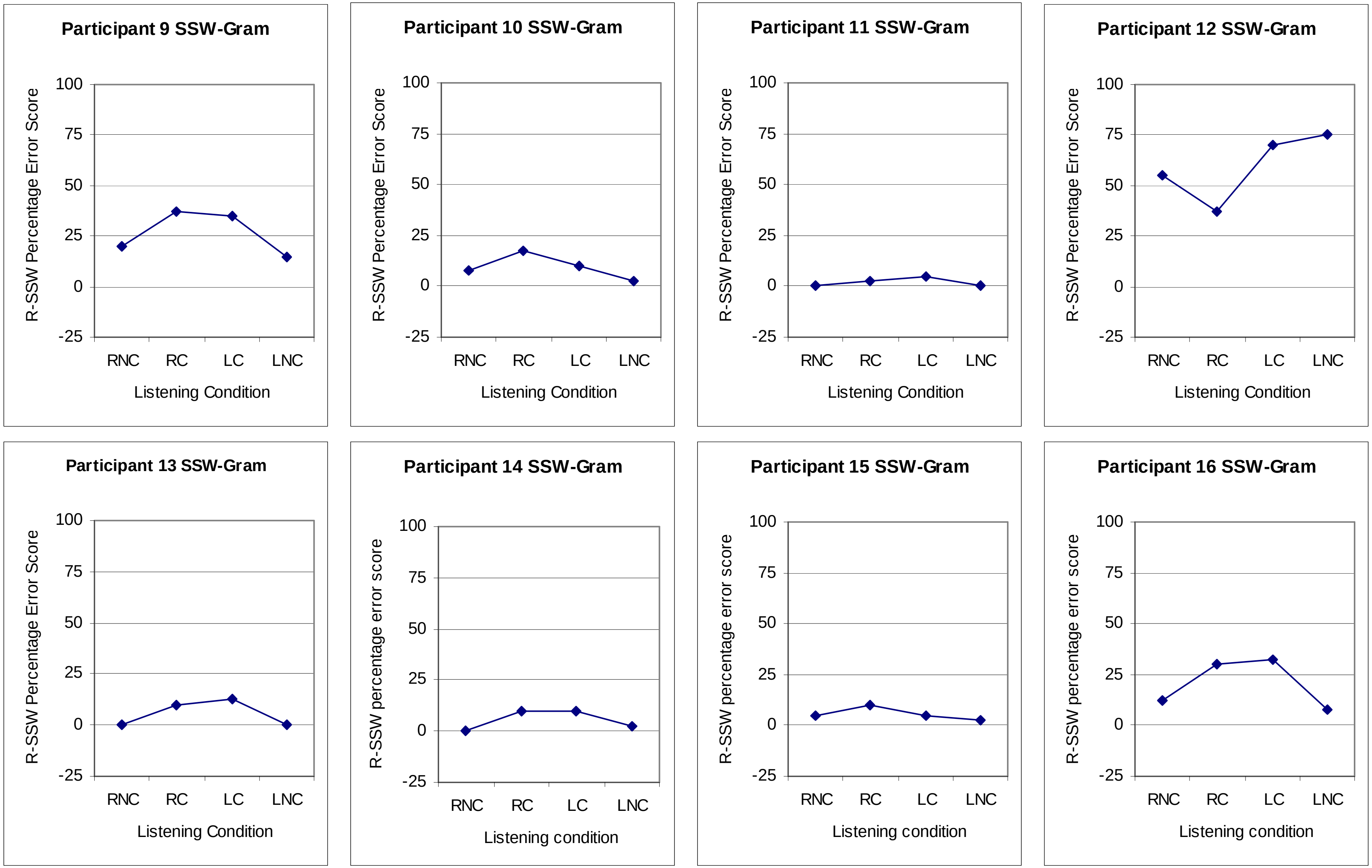
Participant	Single Pairs		Double Pairs		REA
	Left Ear	Right Ear	Left Ear	Right Ear	
1	92	96	92	92	0
2	88	92	77*	70*	-7
3	94	100	96	98	2
4	100	98	97	95	-2
5	94	84*	72*	82*	10
6	100	100	99	100	1
7	95	100	95	96	1
8	65*	85*	57*	89*	32
9	95	100	92	95	3
10	85*	95	83*	90	7
11	90	100	78*	87*	9
12	69*	58*	35*	75*	40
13	100	95	87*	93	6
14	100	100	92	97	5
15	90	95	67*	94	27
16	95	95	94	79*	-15
17	25*	75*	2.5*	95	92.5
18	100	100	93	99	6
19	100	90	90	94	4

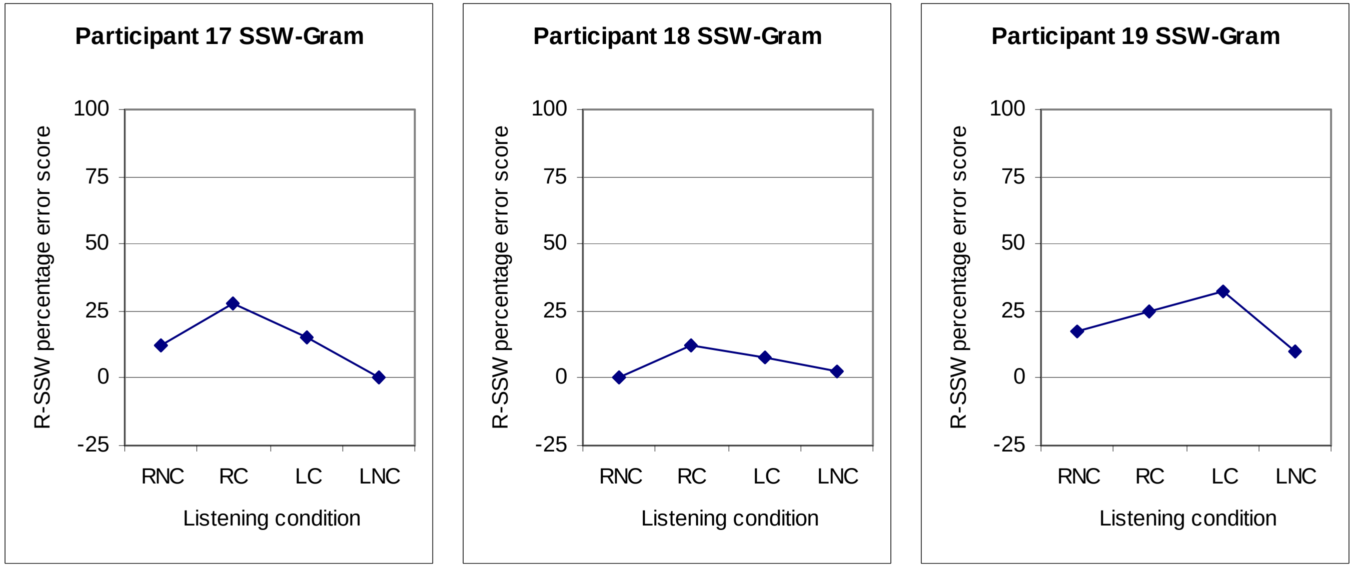
*= Fail

Appendix V

Individual participant R-SSW scores across listening conditions.

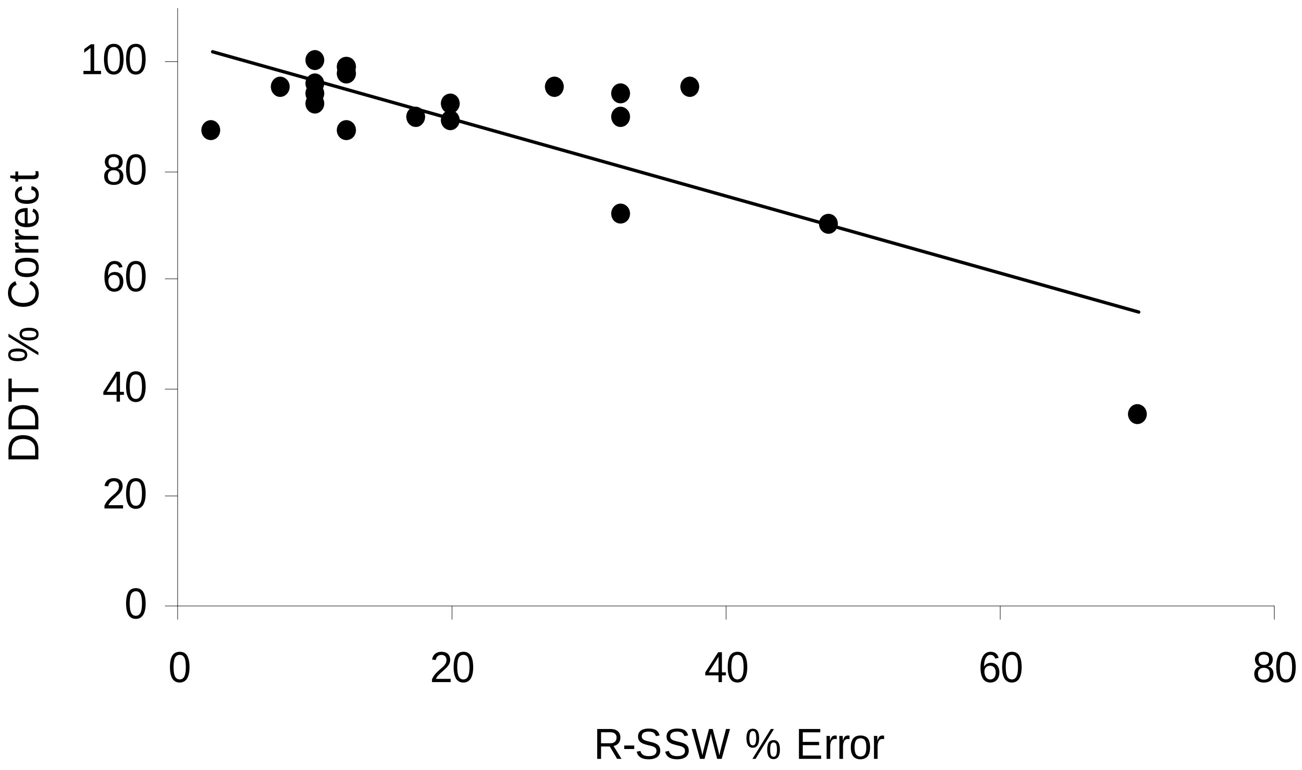



Participant 9 SSW-Gram
R-SSW Percentage Error Score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening Condition
Participant 10 SSW-Gram
R-SSW Percentage Error Score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening Condition
Participant 11 SSW-Gram
R-SSW Percentage Error Score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening Condition
Participant 12 SSW-Gram
R-SSW Percentage Error Score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening Condition
Participant 13 SSW-Gram
R-SSW Percentage Error Score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening Condition
Participant 14 SSW-Gram
R-SSW percentage error score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening condition
Participant 15 SSW-Gram
R-SSW percentage error score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening condition
Participant 16 SSW-Gram
R-SSW percentage error score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening condition


Participant 17 SSW-Gram
R-SSW percentage error score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening condition
Participant 18 SSW-Gram
R-SSW percentage error score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening condition
Participant 19 SSW-Gram
R-SSW percentage error score
100
75
50
25
0
-25
RNC
RC
LC
LNC
Listening condition

Appendix VI

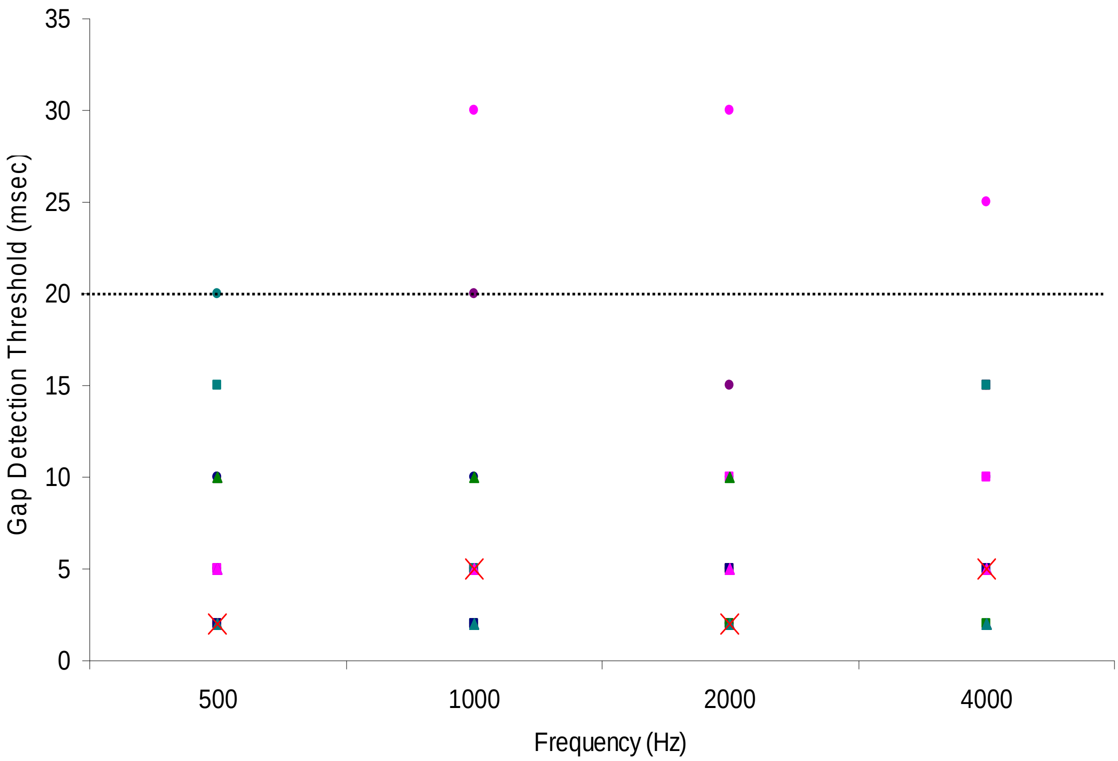
Individual R-SSW scores for the worse competing condition versus Dichotic Digits scores for the same ear.



Statistical analysis revealed a significant negative correlation between R-SSW score and performance on the DDT ($r=-0.793$, $p<0.01$), indicating that those who made fewer errors on the SSW scored more highly on the DDT.

Appendix VII

Individual participant gap detection thresholds across the frequency range.



Random Gap Detection thresholds across the frequency range (dashed line represents the cut-off point for pass criterion (20 msec)).