GAP DETECTION THRESHOLDS IN OLD AND YOUNG ADULTS FOR SPEECH AND NONSPEECH STIMULI DIFFERING IN SPECTRAL PROPERTIES

by

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ABSTRACT

Older adults have more difficulty than younger adults understanding spoken language, especially in the presence of background noise and when the speech signal is degraded (e.g., CHABA, 1988). Such deficits exist even for older adults with audiometric hearing thresholds in the normal range (e.g., Pichora-Fuller, 1997). Temporal processing has been implicated as an important aspect of speech processing that is susceptible to age-related changes. Gap detection tasks measure one aspect of temporal processing by determining the smallest gap between two stimulus markers that can be detected by a listener. Characteristics of gap detection stimuli, including marker duration and spectral symmetry of markers, influence the degree to which a gap detection task approximates processing of phonetically important temporal speech cues. Manipulation of these features has been shown to affect listener performance (e.g., Phillips, Taylor, Hall, Carr, & Mosop, 1997). This thesis examines the influence of such stimulus characteristics on age-related effects in gap detection performance, and considers the implications of such interactions.

Gap detection thresholds were measured for eight younger and eight older normal-hearing adult listeners. The stimuli were varied across three dimensions, which included (1) speech versus non-speech, (2) long duration markers versus short duration markers, and (3) symmetrical versus asymmetrical markers. Gap detection performance was measured for each participant in eight stimulus conditions, which included all possible combinations of the three varied stimulus characteristics.

Results replicated past findings which indicate poorer gap detection performance in older adults compared to younger adults, independent of audiometric hearing loss (e.g., Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994; Snell, 1997). This age difference was shown to be significantly greater when markers were asymmetrical, which is consistent with the view that older adults have particular difficulty in processing temporal cues which closely approximate those found in consonant-vowel combinations in real speech. In asymmetrical conditions, participants of all ages were shown to perform better in speech conditions, indicating the presence of processing cues intrinsic to real speech signals that are independent of the temporal and spectral characteristics matched between the speech and non-speech stimuli used in this study.

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1. LITERATURE REVIEW

1.1 Introduction

Older adults have greater difficulty understanding spoken language compared to younger adults (e.g., CHABA, 1988). These deficits are evident even in elderly listeners without significant cochlear hearing losses, particularly in conditions of background noise and with degraded speech signals (e.g., Fitzgibbons & Gordon-Salant, 1996; Pichora-Fuller, 1997). As advances are made in determining the effects of aging on the mechanisms of auditory speech processing in real-life situations and in locating the levels of the auditory system at which age-related declines occur, communication professionals will be better able to diagnose and treat older people who complain of difficulty understanding spoken language.

While many age-related changes in the auditory system may contribute to problems in speech perception, temporal processing has been recognized to have special relevance for older listeners (e.g., Fitzgibbons & Gordon-Salant, 1995; Gordon-Salant and Fitzgibbons, 1993; Humes & Christopherson, 1991). Temporal resolution, one aspect of temporal processing, is often measured using gap detection tasks. In these tasks, the smallest gap in a stimulus that can be detected by the listener is determined. Importantly, in at least some conditions, gap detection thresholds are larger in older than in younger adults, regardless of degree of hearing loss (e.g., Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994; Snell, 1997).

One of the stimulus conditions that influences the size of the gap that can be detected is the frequency content of the markers surrounding the gap. Specifically, the detection of a gap bound by markers of differing frequency content appears to activate fundamentally different auditory processes than those involved in detecting a gap within a single frequency channel. Phillips, Taylor, Hall, Carr, and Mosop (1997) described the latter process as a discontinuity detection operation within one perceptual channel, and the former as a relative-timing task involving an integration of coding across separate channels. Gap thresholds are consistently higher in the between-channel condition. Phonetically important gaps in speech waveforms typically occur between sounds of different frequency content, and Phillips et al. (1997) suggest that between-channel gap detection may replicate the speech processes that underlying phonemic distinctions, such as stop consonant discrimination based on voice onset time. These findings are promising in that a major objective of gap detection researchers, including those investigating age-related changes in temporal processing, has been to develop stimuli which tap into the mechanisms involved in speech processing.

The main purpose of this thesis is to determine if older adults, who have relatively normal hearing thresholds in the speech range, show decreased performance in between-channel gap-detection relative to younger adults. If an age difference exists, it will lend support to the hypothesis that older adults have reduced ability to use temporal cues in signals which approximate the spectral characteristics of consonant-vowel sequences in speech. In addition, this research will investigate whether gaps in speech, with similar temporal and overall frequency spectrum characteristics as the non-speech stimuli, will be equivalent or not in detectability to the corresponding gaps in non-speech stimuli. If the two types of stimulus are not equivalent, the results would suggest that there are intrinsic mechanisms involved in the processing of real speech in addition to those involved in processing the temporal and frequency characteristics present in non-speech stimuli matched on these dimensions.

The following discussion will first focus on research which has uncovered age-differences in speech perception and temporal processing. A summary of findings in gap detection studies in normal-hearing, hearing-impaired, and older adults will then be addressed. Within-channel gap detection findings will be outlined first, followed by between-channel findings. Models of gap detection, possible explanations of age-related differences, and applicability to real-life speech understanding will also be discussed.

1.2 Speech Perception in Older Adults

In comparison to younger adults, older adults have greater difficulty understanding language spoken in everyday listening situations (e.g., Frisina & Frisina, 1997; Pichora-Fuller, 1997). A report prepared by the committee on Hearing, Bioacoustics and Biomechanics (CHABA, 1988) of the Acoustical Society of America reviewed studies of hearing in the elderly population and proposed a general outline of factors which may contribute to the difficulties older adults have understanding speech, particularly in background noise, and in the presence of multiple talkers. This report suggested that speech perception difficulties in the elderly can be attributed to the influence of elevated audiometric thresholds, cognitive declines, and/or reduced central auditory processing ability. Many studies on hearing in older adults has been guided by the 1988 CHABA report (e.g., Frisina, Frisina, Snell, Burkard, Walton, & Ison, 2001; van Rooij & Plomp, 1992) and researchers have often attempted to separate the possible contributions of these three factors to speech perception in the elderly population. In addition to the differentiating between causal factors of reduced understanding in older adults, many researchers have focused on determining the associated auditory neural sites of biological aging. Overall, hearing researchers have become more careful in establishing strict subject selection criteria when testing speech processing abilities in older adults, especially to control for the influence of audiometric hearing loss on speech processing.

1.2.1 Effects of Hearing Impairment on Speech Perception in Older Adults

The peripheral auditory system is known to undergo deterioration as a result of aging, and it is reasonable to first investigate the effects of typical age-related sensori-neural losses in high-frequency regions on speech recognition performance. Some researchers have proposed that most, if not all, of the difficulties of older adults in understanding spoken language are a product of decreases in audiometric thresholds (e.g., Humes, Watson, Christensen, Cokely, Halling, & Lee, 1994; van Rooij & Plomp, 1992).

In order to measure the relative contribution of audiometric thresholds as compared to cognitive or other auditory processing factors, Humes et al. (1994) measured performance on speech recognition tests using different stimuli (nonsense syllables, monosyllabic words, and sentences), auditory processing tests (Test of Basic Auditory Capabilities), and cognitive tests (Wechsler Adult Intelligence Scale-Revised, and Wechsler Memory Scale-Revised) in fifty older adults (aged 63 to 83 years) who had varying amounts of sensori-neural hearing loss. Testing was carried out in noise and in quiet. In an analysis of associations between these measures, the authors concluded that hearing-loss is the main factor influencing speech-recognition performance in elderly, with auditory processing and cognitive function accounting for little of the variance in word recognition. The authors argue that the results of this study support a view of hearing in aging in which audibility is of primary importance in the understanding of spoken language. They interpret these results as being encouraging in regard to the potential success in a continued focus on using amplification to rehabilitate elderly persons who are hard-of-hearing.

Despite the established influence of age-related audiometric loss on speech perception and word recognition, there is clear evidence that even older adults with relatively normal audiometric thresholds in the speech range have difficulty perceiving speech in real-life circumstances (CHABA, 1988; Pichora-Fuller, 1997), and in experimental conditions in which speech is degraded (e.g., Fitzgibbons & Gordon-Salant, 1995; Pichora-Fuller, Schneider, & Daneman, 1995). In addition, speech perception performance has been shown to decline in adults before audiometric thresholds are significantly reduced (e.g., Bergman, Blumenfield, Cascarado, Dash, Levitt, & Marguiles, 1976).

Other research has determined that decreases in speech processing in older adults are greater than can be accounted for by pure-tone thresholds (e.g., Helfer & Huntley, 1990). In an investigation of the influence of aging and hearing loss on consonant perception in reverberation and noise, Helfer and Huntley (1991) measured identification accuracy and error pattern on the City University of New York Nonsense Syllable Test (Resnick, Dubno, Hoffnung, & Levitt, 1975) for younger normal-hearing adults and older adults with hearing loss or with only minimal hearing loss. Audiometric hearing loss in older subjects did adversely affect ability to identify distorted consonants; however, age was correlated with the perception of several consonant features independent of audiometric hearing loss. These results support the view that additional factors play at least a secondary role to audibility in speech processing in the elderly population.

1.2.2 Cognitive Factors in Speech Perception in Older Adults

Researchers have attempted to measure the extent to which cognitive factors such as use of context, memory, selective attention, and processing speed affect speech processing in older adults (e.g., CHABA, 1988; Frisina & Frisina, 1997; Pichora-Fuller et al., 1995; van Rooij & Plomp, 1990, 1992). Results from a 1990 study by van Rooij & Plomp, utilizing a battery of auditory, cognitive, and speech perception tests, were interpreted as indicating that a general deterioration in mental efficiency, represented in a slowing of processing and reduced memory capacity, accounted for approximately one-third of the variance in speech perception scores. Elevated pure-tone thresholds were found to account for the other two-thirds of the variance. It is worth noting however, that these researchers conducted a similar investigation (van Rooij & Plomp, 1992) with a less homogeneous subject population, and interpreted their results as indicating that cognitive factors were less influential on the variance of speech perception scores than previously indicated, with almost all variation being attributed to audiometric hearing loss (see Section 1.2.1).

Some studies (Frisina & Frisina, 1997; Pichora-Fuller et al., 1995) have found that the ability to use context in word recognition tasks, a cognitive aptitude, does not decline with aging. In a study by Pichora-Fuller et al. (1995), younger normal-hearing listeners and older listeners with high-frequency hearing loss or with normal hearing were measured for identification and recall of sentence-final words in Revised Speech Perception in Noise (SPIN; Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984) sentences presented in a babble background with varying signal-to-noise ratios (S/N). Sentence-final words were either predictable from the sentence context (high-context) or unpredictable (low-context). In the high-context, but not in the low-context situations, the use of working memory could benefit listeners because information from the beginning of the sentence could help the listener identify the sentence-final word. It was hypothesised by the authors that if cognitive abilities accounted for age-differences in word identification, then there would not be an age effect in the low-context condition. In fact, older adults did perform worse than younger adults in the low-context condition. In addition, older adults benefited more from context in more adverse S/N situations that stressed perceptual and memory processes. Neither age-related deterioration in cognitive processing nor elevated audiometric thresholds alone provided an adequate explanation for this pattern of results. The interactions between perceptual and cognitive processing were apparent (see also Schneider & Pichora-Fuller, 2000). These results were in agreement with those of Frisina and Frisina (1997), who also found that older adults use semantic contexts more effectively than young adults when testing on word recognition in background noise. They suggest that the older adults have intact cognitive abilities with impaired sub-cortical neural processing mechanisms interfering with speech perception in background noise.

1.2.3 Effects of Auditory Processing on Speech Processing in Older Adults

Auditory processing deficits, loosely defined as "difficulties in distinguishing between two minimally contrasted acoustic stimuli" (Humes & Christopherson, 1991, pg.687) play a role in speech processing (see also Greenberg, 1996). Such processing difficulties may relate to the use of cues in several physical dimensions of sound stimuli, including frequency, intensity, duration, and location in auditory space.

In addition to assessing the contribution of auditory sensitivity to recognition of nonsense syllables presented in unfiltered, filtered, and reverberant conditions, Humes and Christopherson (1991) set out to determine the contribution of psychoacoustic abilities, including duration, embedded test-tone, and frequency discrimination. Pure-tone thresholds were the primary contributor to recognition scores in all signal distortion conditions, and the other psychoacoustic measures, primarily those involving temporal processing, contributed to the variance of unfiltered recognition scores. Measures of temporal processing will be the focus of this thesis, and will defined and further discussed beginning in Section 1.3.

1.2.4 Interactions between Contributors to Speech Perception in Older Adults

The CHABA (1988) framework for addressing which factors (cochlear hearing loss, cognitive declines, and/or deficits in central auditory processing) most significantly influence the capabilities of older adults to understand spoken language has been employed by many researchers. In truth, these factors are likely inter-related and interact with each other. For example, Schneider and Pichora-Fuller (2001) suggest that as adults age, the perceptual and cognitive domains become more interdependent.

Some researchers have defined their modelling of speech perception in terms of peripheral versus central mechanisms and interactions (e.g., Frisina, 2001; Willott, 1996). Frisina (2001) offers a conceptual framework for examining age-related deterioration in hearing and speech processing which incorporates peripheral hearing loss and central auditory impairments. Within this framework, aging can affect the auditory system directly at the cochlear level, reducing sensitivity to sounds, or at the retro-cochlear level, with neural degeneration of the central auditory nervous system. Frisina also accounts for central changes within the auditory brainstem and cortex which are peripherally induced, resulting from changes in the outputs of the inner ear. Age-related changes in cognition are also assumed to influence the perception of speech sounds in cortical centres.

1.3 Auditory Temporal Processing

A form of auditory processing which has been implicated as being particularly significant in contributing to the difficulties of older adults in understanding spoken language is temporal processing. A definition of temporal processing in hearing research is somewhat elusive insofar as several auditory phenomena can be labelled as being dependent on the listener's temporal processing abilities. For example, pitch perception arising from signal periodicity, spatial auditory perception based on inter-aural time differences, and temporal segregation of successive acoustic events all involve the activation of temporal processes (Phillips, 1995). The focus of this study is on temporal segregation of acoustic events, which is more directly defined as "the ability to detect changes in stimuli over time" (Moore, 1989, pg.137).

The importance of the temporal structure of spoken language is revealed in a study which tested listeners' sentence recognition ability using stimuli limited to four spectral regions of the signal (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). The content of each frequency band of the signal was a band-passed noise with the corresponding amplitude envelope of the filtered sentence. In this condition, listeners achieved near-perfect sentence and phoneme recognition. These results indicate that temporal information in a limited number of spectral regions, in the absence of fine-structure periodicity or synchrony cues, is sufficient to maintain a high level of message comprehension.

1.3.1 Temporal Processing in Older Adults

Evidence of an age-related decline in auditory temporal resolution has come from several studies which have determined that older adults experience greater difficulty in speech recognition tasks when the signal is temporally degraded, particularly with high complexity stimuli and when perceptual processing demands are elevated (e.g., Fitzgibbons & Gordon-Salant, 1995; Gordon-Salant and Fitzgibbons, 1993; Humes & Christopherson, 1991). Distortion of the temporal waveform of speech is produced in several real-life situations, including reverberant conditions, interrupted speech, and fast speech. In such conditions of temporal distortion, the important acoustic cues available in speech are substantially degraded, and a slowing of temporal processing in older adults can exacerbate this situation substantially. A longitudinal study of age-related deficits in speech understanding (Bergman, et al., 1976) indicated that age-related decrements in speech perception are greatest in conditions which increase temporal processing demands. In this study, interrupted speech, reverberant speech, and overlapping word stimuli were utilised. Performance in each of these conditions began to deteriorate in a 40-49 year age group, and this decline was greater for older subject groups. In addition, the average performance for all listeners in temporally degraded conditions assessed seven years following initial testing was worse relative to original performance.

Gordon-Salant and Fitzgibbons (1993) investigated the effect of aging, independent of hearing loss, on the speech recognition difficulties of elderly adults for temporally degraded speech. In this study, three types of temporal waveform distortion (reverberant, time-compressed, and interrupted speech) were imposed on low-predictability SPIN sentences in order to generate psychometric functions that related speech recognition performance to degree of degradation. In addition, auditory temporal processing measures (duration discrimination, gap duration discrimination, gap detection) were compared to the speech recognition measures obtained for all participants. Effects of age and hearing loss were evaluated independently using a participant pool that included normal-hearing younger and older adults as well as hearing-impaired younger and older adults. Percent-correct recognition scores indicated that there was a contribution of age to deficits in speech recognition performance independent of audiometric thresholds in all three of the temporally degraded speech conditions. Temporal processing measures were especially shown to contribute to speech recognition scores in the reverberant condition.

In another study investigating changes in temporal processing in the aging auditory system (Strouse, Ashmead, Ohde, & Grantham, 1998), it was found that, compared to normal-hearing younger adults, normal-hearing older adults performed significantly worse in monaural (gap detection) and binaural (interaural-time difference thresholds) tests of temporal processing, and they also scored worse on two measures of speech perception. However, this study failed to find a significant correlation between individual differences in speech perception and temporal resolution performance. One explanation of the lack of significant association between temporal processing and speech perception is that the stimuli used in this study were not sufficiently speech-like, and/or that speech is processed in fundamentally different ways than non-speech stimuli (Snell & Frisina, 2000; Strouse et al., 1998).

1.4 Gap Detection

A common method of investigating temporal processing, defined as the ability to detect changes in auditory stimuli in the time domain, is to measure the gap detection ability of listeners. The focus of the remainder of this literature review will be on the various designs and results of gap detection studies used to measure temporal resolution. Attention will be directed toward the differing stimulus characteristics in gap detection experiments, models developed to explain the determinants of gap detection performance, and in particular, the changes in gap detection ability of older adults. Temporal processing as measured in a variety of experimental designs, including gap detection tasks, aim to help clarify the mechanisms by which the auditory system encodes temporal features of speech. In addition, it a goal of this research to investigate how these processes may have a unique neural circuitry, follow a distinct developmental time course, and be differentially susceptible to age-related pathologies and the degradation of speech signals encountered in everyday situations.

1.4.1 Within-Channel and Between-Channel Gap Detection

A gap detection threshold is an estimate of the smallest period of silence that allows the listener to accurately distinguish between a test stimulus with a gap and a corresponding stimulus without a gap. Typically, the size of this gap is systematically varied, often using an adaptive tracking procedure, until a gap threshold is determined. The portion of the stimulus preceding the gap is the leading marker, and the portion of the signal following the gap is the lagging marker. A key distinction in gap detection stimuli is the equivalency of these two markers. The discussion in Section 1.5 will focus on studies which have utilised stimuli containing markers with common acoustic features. This design has been termed within-channel, because the markers can be assumed to activate the same sets of neurons in the auditory pathway both before and after the gap. In between-channel gap detection stimuli, the markers differ across one or more of several features, including, for example, spectral content or laterality. A discussion of between-channel gap detection will be presented in Section 1.6.

1.5 Within-Channel Gap Detection

1.5.1 Factors Influencing Within-Channel Gap Detection Ability in Normal-Hearing Adults

The performance of normal-hearing listeners in within-channel gap detection tasks is influenced by a variety of stimulus parameters, including level, bandwidth, and frequency. In general, gap detection thresholds improve with increases in stimulus level up to 40 dB SL (e.g., Fitzgibbons, 1983; but see Schneider, Speranza, & Pichora-Fuller, 1998). It is well known that gap detection thresholds in normal-hearing younger adults decrease with increasing signal frequency for tonal stimuli (e.g., Moore, Peters, and Glasberg, 1993). For tones, the size of the smallest detectable gap is assumed to decrease as the size of the auditory filter increases, with smaller gap detection thresholds being found for higher frequencies where the critical band is larger. For noise stimuli, gap detection thresholds generally decrease with increasing high-frequency cutoff and bandwidth, but these parameters interact such that gap detection thresholds are smallest when the high-frequency cutoff is above about 2 kHz and the bandwidth exceeds about 4 kHz (Snell, Ison, & Frisina, 1994). When noise stimuli involve processing by multiple auditory filters, including filters for higher frequency components, then gap detection thresholds decrease, suggesting that temporal resolution is enhanced by the contribution of processing by these broader high-frequency filters.

Thus, research has determined that in within-channel conditions, gap detection thresholds are best when markers are sufficiently above threshold, broadband, and centred at high frequencies. In these optimal conditions, gap thresholds are typically below 5 ms (Oxenham, 2000).

These empirical findings have been interpreted in terms of more peripheral processing explanations, and more recently in terms of more central processing accounts. Cast in a more peripheral processing account, improved gap resolution at high frequencies may suggest that low-frequency auditory channels show inferior temporal resolving abilities. Possible explanations for this include the confusion of low-frequency envelope fluctuations with the inserted gap, slower decision processes within low-frequency perceptual channels (Phillips et al., 1997), or the relatively narrow cochlear filter at low centre-frequencies which allow longer response times resulting in increased "ringing" following the leading marker offset to obscure the gap (Moore et al., 1993). Further research (Moore et al., 1993; Moore, Peters, & Glasberg, 1992) indicates that the pattern of increases in gap thresholds with decreases in auditory bandwidth at low frequencies is not as would be expected, however, if a simple peripheral auditory filter model was used to explain gap detection performance. Cast in a more central processing account, these findings are likely related to the fidelity of the gap representation and the number of activated neural channels leaving the cochlea (Phillips, Hall, Herrington, & Taylor, 1998). For example, the dependency of gap threshold on bandwidth (Eddins, Hall, & Grose, 1992) may reflect the increased amount of information being transmitted to more central regions of the auditory system (Phillips et al., 1997).

1.5.2. Effects of Cochlear Hearing Loss on Within-Channel Gap Detection

In general, gap thresholds of people with cochlear hearing loss are higher than those of normal-hearing listeners (e.g., Moore & Glasberg, 1988; Tyler, Summerfield, Wood, & Fernandes, 1982). In an analysis and comparison of speech intelligibility in noise and temporal processing in listeners with hearing loss or normal hearing (Tyler et al., 1982), the detection of gaps in noise bursts centred at 500 and 4000 Hz in individuals with cochlear hearing loss were shown to be elevated relative to detection by normal-hearing listeners, and correlated significantly with speech perception measures. In this relatively early gap detection study, the authors suggested that their results indicate that listeners with cochlear loss have impaired forward masking, resulting from extended post-stimulus recovery periods. A longer period of recovery for activated neurons would necessitate a longer gap following the initial marker to allow for a maximal stimulation upon onset of the lagging marker.

As previously stated, gap thresholds for normal listeners decrease as the frequency of the signal increases. Thus, it was suggested that the larger gap thresholds in listeners who are hard-of-hearing may be due to the reduced audibility of high-frequency components. In an investigation of this matter, Moore and Glasberg (1988) measured band-pass noise and sinusoid gap detection performance in both ears of subjects with unilateral moderate cochlear hearing loss. Measurements in the normal-hearing ear were made at the same sound-pressure level as in the impaired ear, as well as at the equivalent sensation level, with background noise present in both conditions to mask spectral splatter. When noise-band gap stimuli were presented at equal SL, as compared to equal SPL, gap threshold differences between hard-of-hearing and normal-hearing listeners were reduced, but not eliminated. These results suggest that enlarged gap detection thresholds cannot be explained in terms of elevations in audiometric threshold. The authors instead propose that fluctuations in the noise bands can create dips in the waveform which become confused with the gap, and that listeners with cochlear hearing loss may perceive a more prominent dip as a result of loudness recruitment.

Fitzgibbons and Gordon-Salant (1987), using broadband noise stimuli, also found that listeners with cochlear loss in frequency regions above 1000 Hz have reduced gap detection performance. Gap detection was tested using noise bands centred at 500, 1000, and 4000 Hz. The listeners who were hard-of-hearing had significantly poorer gap thresholds even in regions with normal pure-tone thresholds (500 and 1000 Hz), indicating that cochlear hearing loss appears to give rise to temporal processing deficits even within regions of normal hearing sensitivity.

1.5.3. Within-Channel Gap Detection in Older Adults

Gap detection measures have been utilised to explore declines in temporal processing associated with aging. Although it is clear that individuals with sensori-neural hearing loss, including a large proportion of the elderly population, have elevated gap thresholds, it is more challenging to determine whether age-related differences in gap detection performance are independent of audiometric hearing losses. Researchers have attempted to recruit older adults with normal hearing in order to eliminate the potentially confounding influence of cochlear hearing loss in studies of temporal resolution and aging.

Moore et al. (1992) compared gap thresholds for normal-hearing younger adults, normal-hearing older adults, and older adults who were hard-of-hearing using sinusoids presented at six frequencies, ranging from 100 to 2000 Hz, at various intensity levels, and in the presence of masking noise. Mean results for the age groups indicated that gap thresholds do not significantly differ between normal-hearing and older adults who are hard-of-hearing, and that both older groups had significantly larger gap detection thresholds than the younger adult group. However, the authors noted that most elderly subjects had gap thresholds within the normal range, and suggested that the mean difference between younger and older adults with normal hearing was a result of a limited number of outlying older subjects with particularly high gap thresholds, thus raising questions about individual differences in auditory processing in the older group.

Other studies have provided further evidence of age-related temporal processing deficits evidenced by reduced gap detection thresholds. For example, Schneider et al. (1994) used Gaussian-enveloped 2000-Hz tone pips to estimate gap detection thresholds in older and younger adults. Older adults had gap detection thresholds which were more variable and approximately twice as large as those of younger adults. Importantly, gap thresholds were independent of audiometric thresholds, indicating that reduce temporal acuity may not be related to degree of cochlear hearing loss. The results from this study were interpreted in terms of older adults having larger temporal windows compared to younger adults. Snell (1997) investigated age-related changes in gap detection thresholds using low-pass noise with either high or low cut-off frequencies. In her study, younger and older adults, who were relatively well matched for absolute audiometric thresholds, were tested in a variety of background noise conditions. Gap thresholds were found to be 27% to 37% higher for older adults, compared to younger adults, over the entire range of stimulus characteristics and background conditions tested, supporting the hypothesis that a generalized age-related decline in temporal resolution exists, and it is independent of audiometric hearing acuity. Interestingly, despite a careful design to minimize possible confounding contributors to age differences (specifically, audiometric hearing loss) Snell's results are in close agreement with that of previous studies of age-related differences in gap detection threshold (e.g., Schneider et al., 1994).

1.5.3.1 Effects of Marker Duration on Within-Channel Gap Detection in Older Adults

As outlined above, a main purpose in measuring temporal processing in older adult listeners is to determine the degree to which these decrements affect the understanding of language spoken in daily situations. With this goal in mind, one stimulus parameter in gap detection testing which is particularly important is the duration of the leading marker. In speech, phonetic markers are typically of short duration, and many of the age-related studies have been carried out using relatively long duration markers. Schneider and Hamstra (1999) examined the effect of leading marker duration on gap detection thresholds in twenty normal-hearing younger adults and twenty older adults with hearing thresholds below 25 dB HL at 2000 Hz. The stimuli were 2000-Hz tone pips with marker durations ranging from 2.5 to 500 ms in the presence of a notched-noise masker centred at 2000 Hz to control for off-frequency listening. The gap detection thresholds of older listeners were significantly larger than those of younger listeners at most marker durations, and were independent of audiometric hearing thresholds at the tested frequency. This age-related difference became less pronounced as marker duration increased up to a leading marker duration of 500 ms where no significant age-related difference was found. The important effect of the duration of the marker on age-related differences in gap detection performance may explain the lack of significant age-related differences in performance found in other studies which used relatively long markers.

1.5.3.2 Within-Channel Gap Detection and Speech Processing in Older Adults

The within-channel gap detection experiments outlined above were carried out as an efficient method of measuring temporal processing abilities, which are implicated as influencing the ability of older adults to understand language spoken in daily situations. Correlations have been found between gap detection ability and more complex perceptual abilities which are of particular interest, namely, speech perception in noise (e.g., Gordon-Salant & Fitzgibbons, 1993; Tyler et al., 1982). For example, in a study previously mentioned, Tyler et al. (1982) measured gap detection thresholds using noise bursts in quiet and they also measured word recognition scores for sixteen normal-hearing younger adults, averaging 23 years of age, and 16 older adults, averaging 53 years of age. By combining data for the two groups and partialing out the effects of pure-tone thresholds, the authors reported a significant correlation between gap detection performance and word recognition. Results from Strouse et al. (1998) are in contrast to Tyler et al.'s findings, insofar as gap detection performance was not found to correlate significantly with speech perception measures for younger and older listeners who had relatively good audiometric thresholds in the speech range. In the study of Strouse et al. (1998), gap detection thresholds were measured using a gated 1000-Hz sinusoid presented at relatively low intensity levels. Despite a lack of correlation between measures, a general age-related decline in both temporal resolution measures and speech measures was found. The authors suggested that stronger correlations may have been found if the measures had been made using more similar stimuli. Other researchers (e.g., Fitzgibbons & Gordon-Salant, 1995) who have carried out similar studies have obtained results which suggest that the limitations in temporal processing in older listeners only become significantly evident with increased levels of stimulus complexity and increased listening task demands.

1.5.4 A Model of Within-Channel Gap Detection

A common model of temporal resolution, which can be utilised to describe within-channel gap detection findings as outlined above, describes four successive processing stages within the auditory system (Moore, 89; Moore et al., 1992, 1993). The components of this model include a bank of band-pass filters, a non-linear device, a low-pass filter or temporal integrator, and a final decision device. The initial band-pass filter array is a representation of the auditory filters, which are very narrow in bandwidth at low frequencies. The non-linear device can be described as a half-wave rectifier which passes only one polarity of the acoustic waveform, or a square-law device which squares waveforms to produce an entirely positive representation of the signal. The next stage acts to smooth the signal such that only slow temporal changes are retained. This is achieved either by a low-pass filter which smoothes the amplitude envelope, or a sliding temporal integrator which acts on the signal energy within a specific temporal window. The output of the window at any instant in time is a weighted average of the energy of the signal over the time period covered by the window. A decision device in the final stage of this model assumes that a gap in the waveform will only be detected if the dip in signal energy reaches a specific threshold value. Such a model provides not only an account of the findings for normal listeners, but it also provides a useful framework for examining the nature of deficits in temporal processing.

1.5.5 Causes of Impaired Within-Channel Gap Detection in Older Adults

The model outlined in the previous section assumes that changes in any of the stages outlined above could affect the temporal processing capabilities of a listener. For example, the auditory filter may play a role in limiting gap detection ability, in that a signal activating a filter with a narrow bandwidth (as found at lower frequencies) will induce higher levels of ringing resulting in a reduced dip in energy (Moore et al., 1992; Schneider & Hamstra, 1999). The presence of a broader temporal window will also result in decreased gap detection ability because a dip in energy will be more shallow relative to the total averaged energy within the window (Moore, 89; Schneider & Hamstra, 1999). From this, it has been suggested that either age-related narrowing of filter bandwidth or widening of the temporal window width could explain the reduced temporal processing abilities in older adults evidenced by gap thresholds increases. The former of these candidates is unlikely, however, as filter bandwidths have not been shown to correlate with gap thresholds (Moore et al., 1993), and aging would be associated with broadening of filter which, if anything, ought to serve to improve gap detection thresholds (Glasberg, Moore, & Bacon, 1987; Pichora-Fuller & Schneider, submitted). Increases in the temporal window are also unlikely to account for age-related reductions in gap detection performance, as Schneider et al. (1998) found that gap thresholds were equally elevated in younger and older adults when the on and off ramping of the Gaussian envelope of the marker tone was slowed. If temporal window size were larger in older adults, then the dip in energy required to detect a gap would have been reduced with slowed ramping, resulting in a reduced age-difference in that condition.

Another possible explanation for the measured age-related differences in gap thresholds is that older adults require a larger energy dip from the temporal window in order to detect a gap. This possibility was explored by Schneider and Hamstra (1999) who hypothesised that in a linear filter model, the response of a filter to a gap is independent of the duration of the tone preceding the gap. If older adults require larger dips in energy, then their gap detection performance should be poorer than that of younger adults at all marker durations. As previously discussed, the results from this experiment showed that, using a 2000-Hz stimulus tone, with marker durations ranging from 0.83 and 500 ms, relatively normal-hearing older adults had significantly higher gap thresholds on average than did normal-hearing younger adults for marker durations of less than 250 Hz but that the two age groups had equal gap thresholds at 500 Hz.

An alternative model to account for the age-related changes in gap detection threshold is based on the role of neural adaptation (Schneider and Hamstra, 1999). The sequence of neural events in response to the acoustic waveform associated with a gap stimulus include a large transient response at the onset of the leading marker followed by a decrease in response rate over time until an asymptotic steady state is reached (adaptation). The offset of the leading marker will result in a rapid drop in relative firing rate, which is followed by a second large transient response accompanying the onset of the lagging marker. Schneider and Hamstra (1999) propose that older adults may have a less efficient recovery from neural adaptation following the first marker which results in decreased strength in the transient response at the onset of the lagging marker. As gap size becomes smaller, less time is available for recovery from adaptation and the gap duration at which recovery from adaptation is no longer sufficient to allow the listener to detect the transient coinciding with the trailing marker is reached sooner for older adults. This model can explain marker duration effects insofar as shorter leading marker durations allow less time for neural recovery following the initial onset transient of the leading marker, reducing the strength of the response to the trailing marker. Older adults, with less rapid recovery from adaptation, will have greater difficult detecting a gap in these conditions. This is particularly important because phonetically important speech sounds are of relatively short durations.

1.6 Gaps in Word Discrimination

In spoken language, the voice waveform contains periods of silence or reductions in amplitude which often indicate phonetically important distinctions. For example, the presence or absence of a consonant can be indicated by the duration of a gap. For example, the word 'split' can be distinguished from the word 'spit' when a gap of sufficient length is inserted between the fricative and liquid (Haubert, 1999; Summerfield, Baily, Seton, & Dorman,1981). It should be noted that gap size does not act alone to cue the presence of a consonant in these conditions. Summerfield, Baily, Seton, & Dorman (1981) determined that length of frication, rate of offset for the word-initial fricative, and frequency of the first format of the vowel can also influence the listener's perception of a stop consonant. Thus, measures of temporal processing must be considered together with other important perceptual processing of temporal and spectral domain cues in word identification.

In order to minimize the contribution of cues other than gap size, specific phoneme contrast may be tested, with perception of contrasts based on voice onset time

(VOT) being common. VOT is measured as the time between a stop consonant burst and voicing of the following vowel, and the duration of this period of reduced energy determines whether a voiced or voiceless stop is perceived. Longer VOTs are associated with voiceless stop consonants. Studies of such phoneme distinctions based on gap size involve presenting speech stimuli to listeners in which gap sized is varied on a continuum from no gap to a large gap. A perceptual boundary is demarcated when the gap size is reached at which there is an equal chance that a listener will perceive the phoneme typically associated with or without a significant gap.

1.6.1 Age Effects on Phoneme Distinctions Based on Gap Size

In an aging study using a VOT continuum ranging from 0 ms (/ba/) to 60 ms (/pa/), Strouse et al. (1998) found that young and older normal-hearing listeners identified distinct phoneme categories at similar phonetic boundaries (27 ms for younger adults, and 32 ms for older adults). Importantly, the identification slope was shallower for older adults, indicating that older adults had a greater percentage of incorrect phoneme identification at VOT values surrounding the phonetic boundary. This is additional direct evidence that older adults may have reduced perception of temporal changes in real speech stimuli, regardless of cochlear hearing loss.

Instead of examining contrasts based on VOT, Haubert (1999) carried out a study in which younger and older adults with relatively normal audiometric hearing thresholds distinguished between word-pairs on a continuum which varied in terms of the duration of a gap which, at large values indicated the presence of a consonant (e.g., 'catch') and at small values, did not result in the perception of a consonant (e.g., 'cash'). The word boundary for older adults occurred at longer gap durations in all conditions, indicating a reduced ability to resolve phonetically important temporal gaps. This difficulty for older adults occurred in fast and slow speaking rate conditions, and was found to correspond to an age-dependant elevation in gap detection thresholds using within-channel markers centred at 2000 Hz.

1.6.2 Non-speech Gap Detection and a Model of Gap Processing in Speech

As is made clear in the analysis of within-channel gap detection studies, methodological variations and stimulus variables influence overall performance and differentially expose age-related effects in gap detection thresholds. As previously discussed, different degrees of correlation between gap detection ability and speech perception have been found. Strouse et al. (1998) suggest that studies which fail to find such a correlation may indicate that the mechanisms underlying detection of temporal gaps may be fundamentally different from those underlying the ability to distinguish the temporal characteristics of speech. However, other explanations concerning the importance of the degree of similarity of the non-speech and speech stimuli used to obtain the measures being compared remain to be ruled out.

A logical goal of some researchers studying gap detection thresholds has been to create gaps in non-speech stimuli which more closely approximate the cues serving the detection of important temporal distinctions in speech. Gap detection stimuli have typically been used to measure within-channel temporal processing, whereas phonemic distinctions in speech typically involve between-channel processing, for which the markers surrounding the gap are spectrally different. For example, VOT distinctions are based on processing of a period of reduced amplitude between a wideband consonantal burst with high-frequency energy and a primarily low-frequency vowel energy. Detection of a gap between these two markers may involve different underlying perceptual mechanisms than in the within-channel case. Thus, it is hypothesised that employing between-channel stimuli in gap detection studies may enhance correlations between psychophysical and speech performance (Schneider & Pichora-Fuller, 2001).

1.7 Between-Channel Gap Detection

The following sections outline results from temporal processing studies in participants who are normal-hearing or hard-of-hearing using between-channel gap detection stimuli. Implications for applicability to speech processing and age-related effects will be discussed.

1.7.1 Between-Channel Gap Detection Measures in Normal-Hearing Adults

Gap detection thresholds for between-channel stimuli, in which the leading and lagging marker of the signal are of differing frequency composition, are significantly larger that those found in within-channel conditions (e.g., Fitzgibbons, Pollatsek, & Thomas, 1974; Formby, Barker, Abbey, & Raney, 1993; Phillips et al., 1997), lending support to the hypothesis that performance in these two conditions are regulated by different perceptual mechanisms. In an early study, Fitzgibbons et al. (1974) found that for short gap durations, normal-hearing listeners had significantly greater difficulty detecting a gap between tones of dissimilar frequency than between tones of equal frequency. The authors interpreted these results as suggesting that increased processing time is necessitated by an attention shift within the frequency domain.

Phillips et al. (1997) found that gap stimuli with a narrowband noise leading marker centred at 2000 Hz produced small gap thresholds in normal-hearing listeners, in the range of 5.3 to 6.3 ms, when the lagging marker was of the same frequency content (within-channel condition). As the centre frequency of the lagging marker became more disparate from the leading marker (between-channel condition), the gap detection thresholds increased significantly, reaching values as high as 45 ms at maximal disparity, at which markers differed by two octaves. Importantly, there was also a greater degree of individual variability in the between-channel conditions. The authors suggest that the underlying perceptual mechanisms responsible for gap detection with equal frequency markers are different from the mechanisms which regulate gap detection with markers of differing frequencies. Within-channel gap detection is described as discontinuity detection because identical sets of neurons within a perceptual channel are activated by both markers. On the other hand, between-channel gap detection requires the integration and comparison of activity in different perceptual channels, requiring a relative timing operation to be performed to accomplish the needed comparison of channels (Phillips et al, 1998; Phillips, Hall, & Carr, 2000; Taylor, Hall, Boehnke, & Phillips, 1999).

Formby et al. (1993) measured gap detection thresholds using leading markers with centre frequency, bandwidth, level, and duration measures which simulated the second formant properties of voiceless stop consonants (/p, t, k/). These leading markers were paired with lagging markers which simulated vowels sounds. Gap detection thresholds of normal-hearing listeners revealed that increases in the difference between the second formant frequencies of the simulated stop consonant and vowel resulted in larger gap thresholds. Differences between other stimulus features (bandwidth, level, duration) did not significantly affect gap detection thresholds. The authors interpret these findings by considering the processing of VOTs following voiceless stop consonants. The authors argue that the perceptual requirement for a relatively large gap separating spectrally disparate stop-vowel combinations matches the longer co-articulatory gesture required in such stop-vowel combinations in the transition from the stop to the second format of a vowel. In essence, the co-articulatory delays may provide processing time that is required by the auditory system to detect temporal changes across frequency.

1.7.1.1 Effects of Marker Duration on Between-Channel Gap Detection

In their 1997 study, Phillips et al. also evaluated the effect on gap detection thresholds in normal-hearing listeners when the duration of the leading marker was varied in within-channel conditions consisting of equal frequency narrowband markers of 1000 or 4000 Hz, and in between-channel conditions containing a 4000-Hz leading marker and a 1000-Hz lagging marker. Leading marker duration was varied from 5 to 300 ms. These authors found that gap detection thresholds were increased with reductions in leading marker duration only in the between-channel condition. In an additional experiment presented in the same paper, Phillips et al. (1997), with the intention of tapping into mechanisms underlying stop consonant discrimination, designed the stimuli to more closely resemble the frequency structure of a consonantal burst followed by a vowel. Varying the duration (5 to 300 ms) of a wide-band noise leading marker preceding a 1000-Hz band-pass noise lagging marker, gap thresholds were found to increase with shorter leading duration. Interestingly, at short leading marker durations of 5-10 ms, the mean gap detection threshold was 32.4 ms, approximating the voice onset time that discriminates between some voiced and voiceless stop consonants (e.g., Strouse et al., 1998). These results were interpreted to have positive implications regarding the possible relationship between gap detection measures using non-speech between-channel stimuli and the processing of phonemic speech cues.

In contrast to the findings of Philips et al. (1997), Grose, Hall, Buss, & Hatch (2002) found that between-channel gap discrimination threshold measures were lower when the leading marker was 50 ms compared to 300 ms, and the effects of leading marker duration did not significantly differ between the within-channel and between-channel conditions. In this study, these researchers re-namede the task as gap discrimination as opposed to gap detection because the listener must discriminate between a stimulus with a standard gap size and one with a larger gap size. Motivation for utilising this method is based on the fact that when tones are shaped with rise/fall ramps to limit the spread of excitation, a temporal transition can be detected despite a lack of an inserted gap. The discrepancy in duration effects found by Phillips et al. (1997) and Grose et al. (2002) may reflect the use of relatively long standard gaps by Grose et al., as opposed to the reportedly inaudible gaps used by Phillips et al. In addition, the shortest leading marker duration used by Grose et al. was 50 ms, whereas Phillips et al. found the largest effects at smaller durations, with maximal thresholds at leading marker durations of 5-10 ms.

In summary, gap detection thresholds measured for normal-hearing adults are significantly elevated and more variable when the leading and lagging stimuli markers differ in terms of frequency content, and increased disparity between marker frequencies and shortening of the leading marker result in decreased between-channel gap detection performance. Investigations have indicated that between-channel gap detection taps into a fundamentally different, more complex measure of temporal processing compared to within-channel gap detection, and important parallels have been found in comparisons of between-channel gap detection measures to the detection of phonemic speech cues (e.g., Phillips, et al., 1997; Formby et al., 1993). These findings have created an impetus to utilise between-channel gap detection in investigating the effects of audiometric hearing loss and/or aging on speech perception. Section 1.7.2 will address the effects of hearing impairment on between-channel gap detection. There has been little or no direct research on the effects of aging on between-channel gap detection, and this is the main goal of the current thesis. The importance of conducting such an investigation is detailed in Section 1.7.5.

1.7.2 Effects of Hearing Impairment on Between-Channel Gap Detection

The impact of cochlear hearing loss on temporal acuity, as measured with between-channel gap detection stimuli has been shown to be significant. Grose and Hall (1996) found that gap detection performance for listeners with cochlear hearing impairment showed a greater reduction as a result of an increase in frequency disparity between 75-ms toneburst markers in comparison to the performance of normal-hearing listeners. Relative to within-channel gap detection thresholds, between-channel performance worsened by a factor of five in the normal-hearing group and a factor of nine in the group with cochlear loss. These results are in agreement with the findings of

Fitzgibbons and Gordon-Salant (1994) that listeners with cochlear loss performed more poorly in detecting gaps than did normal-hearing listeners when markers bounding a 6.4-ms gap were shifted apart in frequency by about one-third of an octave. The results of these studies suggest that listeners with elevated pure-tone thresholds resulting from cochlear hearing loss have increased difficulty with temporal processing that involves comparisons across disparate frequency regions.

Grose et al. (2002) measured within-channel gap discrimination ability with 1035- Hz markers, and between-channel gap discrimination with a leading marker of 2188 Hz and a lagging marker of 432 Hz, in listeners with and without cochlear hearing loss. The standard gap durations, from which the listener had to discriminate a larger gap stimuli, were 35 ms and 250 ms. Results indicated that gap discrimination performance was poorer for across-frequency marker conditions compared to iso-frequency conditions for all participants and at both standard gap durations. However, in disagreement with past results (Fitzgibbons & Gordon-Salant, 1994; Grose & Hall, 1996), findings indicated no effect of hearing loss on gap detection performance. The authors suggest that this disagreement may be because of the relatively long gap intervals used in their study, or else because of an age factor since cochlear hearing loss participants tended to be older in the other studies. Interestingly, Grose et al. (2002) did find an age effect in both within-channel and between-channel conditions, with younger normal-hearing listeners (mean age of 30.5) achieving consistently better gap detection performance than older normal-hearing listeners (mean age 50.3).

1.7.3 Between-Channel Gap Detection across Other Perceptual Dimensions

As previously discussed, Phillips et al. (1997) interpreted larger gap thresholds in conditions with markers differing in frequency content to indicate that auditory processing in such conditions involves an integration of activity within two or more independent frequency channels. To test this hypothesis, Formby, Gerber, & Sherlock (1998) measured gap detection thresholds as a function of frequency separation using a leading sinusoid marker presented to the one ear, and a lagging sinusoid marker presented either to the same ear (monotic condition), or to the other ear (dichotic condition) of normal-hearing adult listeners. In the latter conditions, the gap detection task must involve the combining of input from separate channels (from each ear) at a central location within the auditory system, regardless of frequency equivalency between markers. Results showed that in the dichotic condition average gap detection thresholds were only slightly elevated by increases in marker frequency separation, and even in conditions of similar frequency between markers, gap thresholds were in the range of 30 to 40 ms, which matches the monotic gap detection thresholds in conditions of frequency separation of at least half an octave. This study lends support to the suggestion that a central mechanism is involved in the processing of input from peripheral sources in the detection of temporal cues in signals with varying frequency content. The specific site or sites in the auditory system at which this processing may take place must correspond to a place of interaction among the activated channels.

In a recent study, Grose, Hall, Buss and Hatch (2001) set out to determine if diminished performance in across-frequency gap detection is a manifestation of a more general reduction in temporal resolution caused by perceptual dissimilarity between markers. The authors measured gap detection thresholds for narrowband stimuli using markers which differed in the presence and degree of frequency and amplitude modulation. Results indicated that perceptual discontinuities restricted to an equivalent frequency region did not uniformly elevate thresholds. In a second experiment, gap thresholds were measured for markers differing in bandwidth, duration, and pitch. Thresholds were not sensitive to pitch differences between markers, but were elevated when bandwidth differed between markers, even when the spectral content of the narrow-band marker fell within the spectral range of the wide-band marker. Thus, gap detection was affected by spectral dissimilarity between markers in addition to spectral discontinuity.

1.7.4 Modelling Between-Channel Gap Detection

Fitzgibbons explained the between-channel gap detection operation as involving a shift of attentional processes from the perceptual channel activated by the leading marker to the channel activated by the lagging marker. If this operation of shifting attention is time consuming, it can explain the poorer temporal acuity in between-channel conditions compared to within-channel, and would be susceptible to general cognitive declines associated with attentional processes. Phillips et al. (1997) assume that attentional processes act at a lower level in the auditory system and that the allocation of perceptual resources to one channel will impair the detection and time stamping of events in another channel. In addition, Phillips (1999) argues that between-channel gap detection must take into account complete central neural representations of stimulus elements since there are no neural mechanisms at the auditory periphery able perform the relative timing operations which act on the offset of the initial marker and the onset of the following marker, thereby activating distinct perceptual channels. Results from gap detection studies using similar frequency markers presented to different ears (Formby et al., 1998) indicate thresholds similar to frequency-disparate marker findings, supporting the conceptualisation of a centrally located timing mechanism.

1.7.5 Between-Channel Gap Detection in Older Adults

To date, there have been few, if any, direct experimental investigations into the effects of aging on between-channel gap detection. In attempting to uncover the perceptual mechanisms which are associated with or responsible for declines in speech processing in older adults, a prime objective in the present research is to develop stimuli which tap into the crucial temporal processes that operate in speech processing and word recognition. It is clear that the perceptual mechanisms underlying important phonemic speech sound distinctions, such as VOT, must rely on timing operations performed across frequency channels. The results of Phillips et al. (1997) have indicated that stimuli approximating the frequency and temporal structure of a stop consonant-vowel pairing have resulted in gap thresholds in normal-hearing listeners which may tap into a natural psychophysical boundary which distinguishes between voiced and voiceless stop consonants. In addition, the recent results from Grose et al. (2002) have indicated that, despite a lack of influence of cochlear hearing loss on between-channel gap discrimination thresholds, there appears to be a signify effect of age on between-channel measures of temporal processing.

The main goal of this thesis is to investigate whether there are age-related differences in temporal processing, independent of audiometric hearing loss, as measured by ability to detect a gap in non-speech stimuli with spectral content similar to speech, and with actual speech stimuli. Secondary goals are to compare these between-channel findings to those found in within-channel conditions, and to investigate general and age-dependant effects of changing leading marker duration.

1.8 Hypotheses

Null hypothesis 1. Gap detection ability measured with leading and lagging markers of equal frequency will not significantly differ from gap detection ability measured when leading and lagging markers are of different frequency composition.

Accompanying Research Hypothesis and Prediction. Gap detection ability will be poorer when the leading and lagging markers are of differing frequency compared to that measured with markers of equal frequency composition. This hypothesis is based on several research findings which indicate that the minimal detectable silent gap bound by markers of differing frequency composition is larger than that measured when the markers are spectrally equal (e.g., Fitzgibbons et al., 1974; Formby et al., 1993; Phillips et al., 1997).

Null hypothesis 2. Gap detection thresholds measured using stimuli based on recorded natural speech will not be significantly different from those measured with non-speech, computer-generated stimuli with similar spectral content.

Accompanying Research Hypothesis and Prediction. Gap detection performance will be enhanced with real speech stimuli as compared with gap detection ability measured with non-speech stimuli. Such a finding would indicate that there are inherent cues in speech, distinct from frequency spectrum and energy composition, which enhance the listeners' ability to identify rapid temporal changes in the signal (e.g., Strouse et al., 1998). Cues which are contained in speech that are not present in the computer generated markers may include a harmonic structure which is generated by the vocal tract and cross-correlated to a fundamental frequency (e.g., Greenberg, 1996).

Null hypothesis 3. The effect of marker duration on gap detection thresholds will not differ between older normal-hearing adults and younger normal-hearing adults.

Accompanying Research Hypothesis and Prediction. Gap detection thresholds of normal-hearing older adults will be significantly larger than those of younger adults in the short duration (40 ms) marker conditions, but not in the long duration (250 ms) conditions. This outcome is predicted based on Schneider and Hamstra's (1999) finding that the temporal resolution of older adults, as measured by gap detection thresholds, is poorer than that of younger adults only when marker durations are below 250 ms. In the 500-ms marker conditions, it is expected that gap detection ability will not significantly differ between age groups. This prediction is limited to the symmetrical markers conditions, since the referenced study used only within-channel stimuli.

Null Hypothesis 4. In the presence of a significant reduction in gap detection ability for older normal-hearing adults relative to younger adults in short duration conditions (i.e., confirmation of research hypothesis 3), the said effect will not differ between spectrally symmetrical and asymmetrical stimuli.

Accompanying Research Hypothesis and Prediction. The reduced gap detection ability for older normal-hearing adults relative to younger adults in short marker duration conditions will only be significant in symmetrical stimulus conditions. This prediction follows the explanation of age-related duration effects postulated by Schneider and Hamstra (1999), which suggests that reduced performance in short marker duration conditions can be explained by a temporal window model which incorporates the effects of neural adaptation and adaptation recovery. Employing this paradigm, a gap stimulus which is spectrally asymmetric will not activate a homogeneous neural set, and thus would not be susceptible to the same limiting factors of neural adaptation and adaptation recovery.

Null Hypothesis #5. Overall, the gap detection thresholds of older normal-hearing adults will not differ from that of younger adults.

Accompanying Research Hypothesis and Prediction. Older adults will have larger gap thresholds overall, in comparison to younger adults. This prediction is based on past research which indicates an age-related decline in temporal processing as measured with gap detection thresholds, especially in conditions of increased signal complexity (e.g., Moore et al., 1992; Schneider et al., 1994; Snell, 1997). The degree of signal complexity utilised in this study is expected to be sufficient to demonstrate such an effect of aging.

Null Hypothesis #6. Older normal-hearing adults will have gap thresholds in the asymmetrical marker conditions that do not differ from those of younger adults.

Accompanying Research Hypothesis and Prediction. Older adults will have larger gap detection thresholds in the asymmetrical marker conditions relative to the gap detection thresholds of younger adults. This prediction follows from research which indicates that aging is associated with decreases in speech perception (e.g., CHABA, 1988; Pichora-Fuller, 1997), and the fact that asymmetrical gap marker stimuli better approximate the spectral configuration of phonemic speech distinctions which rely on gap detection. This prediction is also supported by the fact that gap detection thresholds measured using asymmetrical markers approximate VOT boundaries in spoken language (Phillips et al., 1997), and older adults have been found to have compromised skill in utilising VOTs to distinguish phonemes (e.g., Haubert, 1999; Strouse et al., 1998).

Null Hypothesis #7. The effect of stimulus type (speech versus non-speech) on gap detection thresholds, if present, will not be dependant on age.

Accompanying Research Hypothesis. The null hypothesis will be rejected if an effect of stimulus type is found to be dependant on age group (younger or older adult). This will be confirmed if either the younger or older group are found to have gap detection thresholds which are made better or worse in conditions of speech or non-speech stimuli, in the absence of such an effect in the other age group.

2. METHODS

2.1 Objectives

The present study was designed to determine whether or not older and younger adults with normal audiometric hearing in the speech range differed in their ability to detect gaps in speech and non-speech sound stimuli. Two characteristics of the speech and non-speech stimuli, duration and spectral composition, were varied to determine whether or not they would affect gap detection performance and if such effects would depend on age. First, gap detection thresholds were measured using short and long marker durations in an attempt to replicate past findings that older adults perform more poorly than younger adults with short duration markers (Schneider & Hamstra, 1999). Second, the frequency composition of the stimuli was varied in order to determine if within-channel and between-channel gap detection would differ and if any such differences depend on age. Gap detection stimuli in the asymmetrical[1] (between-channel) marker condition are more typical of the signal involved in many consonant-vowel combinations encountered in everyday spoken words, while the symmetrical (within-channel) condition corresponds to VCV patterns where the initial and final vowels are the same and the consonant is a stop consonant. The participants, materials, stimuli, and procedures used to meet the stated experimental objectives are described below.

[1] The "symmetrical" and "asymmetrical" stimulus conditions are labelled so based on the equivalency of frequency content between stimulus markers, and correspond to the often used labels "between-channel" and "within-channel", respectively (see section 1.7.1). In this thesis, these descriptive labels are used in the methods and results sections because they do not assume an underlying model in which distinct perceptual channels are implicated in the processing of markers differing in frequency content.

2.2 Participants

Sixteen listeners participated in this study; eight younger adults (aged 21 to 35 years, mean=26.13 years, SD=4.22 years) and eight older adults (aged 71 to 81 years, mean=75.75 years, SD=4.56 years). Participants in the younger group were recruited from the University of British Columbia community. Participants in the older group were recruited from community and athletic centres in close proximity to the university campus. Participants in both age groups were paid an honorarium of $10 per hour of testing (see Appendix A). All listeners were native English speakers and had normal audiometric hearing in the speech range. In order to be defined as having normal-hearing, participants were required to have pure-tone air-conduction thresholds of 25 dB HL or better from 250 Hz to 3000 Hz in both ears, the absence of a conductive component of hearing loss marked by air-bone gaps of above 15 dB, and the absence of interaural threshold asymmetries greater than 15 dB. Audiometric pure-tone thresholds and a summary of participant characteristics including pure-tone average, speech recognition threshold, age, and years of education are provided in Appendix B, and Appendix C, respectively.

2.3 Materials

Each participant completed a consent form, a Hearing and Language History questionnaire, and the Mill Hill vocabulary test (Raven, 1938).

The main experimental materials in this study consisted of eight sets of gap detection stimuli, each unique in their combination of three experimentally varied characteristics: speech versus non-speech, short versus long marker duration, and symmetrical versus asymmetrical spectral composition. The following sections outline the preparation, description, and calibration of these stimuli.

2.3.1 Preparation and Description of the Gap Detection Stimuli[2]

Non-speech stimuli were constructed digitally at a sampling rate of 20,000 Hz and converted to analog using a Tucker Davis System III digital-to-analog converter. For tonal, non-speech leading and lagging markers, centred at a frequency of 500 Hz, amplitude envelopes were constructed by summing a temporally spaced series of Gaussian envelopes. The standard deviation of these envelopes is 0.5ms, and they are spaced 0.5 ms apart, resulting in a summed envelope with a flat, normalized peak amplitude and matched rise and decay times at the onset and offset of the marker. The time between the peaks of the first and last Gaussian envelope in a marker determines the marker length. The leading marker in non-speech, asymmetrical conditions is a broadband noise digitally filtered to include spectral content from 1000 to 6000 Hz.

The speech stimuli were constructed from recorded samples of [s] and [u] spoken by an adult female research assistant (Anne Marie Bowes). These samples were recorded in a double-walled, sound-attenuating IAC booth using the sound recording program in the Computer Speech Research Environment 4.5 (CSRE 4.5, 1995). The samples were recorded using a Sennheiser model K3U microphone positioned approximately six inches from the talker's mouth. Recorded speech samples were stored on a computer hard drive and subsequently stored on a recordable compact disc. The speech gap-detection stimuli

[2] The specification and preparation of the stimuli used in this study were determined and accomplished co-operatively by Kathy Pichora-Fuller at the University of British Columbia, Bruce Schneider at the University of Toronto at Mississauga, and Stan Hamstra at the University of Toronto and Nancy Benson at the Hospital for Sick Children so that they could be used in the present study as well as in parallel studies being conducted in Toronto on children with dyslexia.

were attenuated or amplified in order to match the total energy content of the corresponding markers used in the non-speech conditions[3].

The speech and non-speech stimuli varied across two additional dimensions: marker duration and spectral symmetry.

In each condition of presentation of the non-speech or speech stimuli, the duration of both the leading and lagging markers was either short (40 ms) or long (250 ms).

Spectrally, the markers in each condition were either equivalent or different in frequency composition, thereby creating the symmetrical and the asymmetrical conditions, respectively. For non-speech stimuli in the within-channel condition, the leading and lagging markers were both 500 Hz tones, and in the between-channel condition, a broadband 1000 to 6000 Hz leading marker was followed by a tonal 500 Hz lagging marker. For speech stimuli, in the within-channel condition, the markers were both [u], with the spectral content being primarily low-frequency and with tone-like formant structure, and in the between-within channel condition, the leading marker was [s] with broadband spectral content followed by [u] with more tone-like formant spectral composition.

Thus, in the present study there were a total of three stimulus variables; speech versus non-speech, symmetrical versus asymmetrical frequency composition of markers, and long versus short marker duration. All possible combinations of these variables resulted in eight stimulus conditions, and thus eight sets of gap detection stimuli were

[3] The duration of each marker in the speech stimuli was held constant in order to maintain the structure of the waveform, and to eliminate single marker duration as a cue for detecting which stimulus in each presentation pair contained the gap. As a result, although single marker duration was held constant, the overall duration of the speech stimuli was increased when a gap was introduced. This situation did not arise with the non-speech stimuli, for which overall duration was held constant. A visual representation of the waveform and spectrogram of speech and non-speech stimuli in each presented condition is provided in Appendix D.

prepared and utilised in testing. Participants in both younger and older adult groups were tested in each of these eight conditions. Time waveforms and spectrograms of example gap stimuli from each condition are provided in Appendix D.

2.3.2 Calibrating the Sound Level of the Gap Detection Stimuli

Presentation levels for the gap detection stimuli were measured for the four long duration stimulus conditions. For this calibration, the gap detection stimuli were presented using the exact experimental apparatus and settings that would be used for experimental testing, as outlined in Section 2.4.1. The level of each stimulus was measured using a sound-level pressure meter coupled to the Sennheiser HD-265 headphones inside a double-walled sound-attenuating IAC booth. The right and left headphones were individually calibrated, since stimulus presentation was binaural. Peak sound-level values measured during the presentation of the long marker duration stimuli, and averaged over both headphones, were 72.8 dB SPL, 70.2 dB SPL, 75.0 dB SPL, and 75.2 dB SPL, for the symmetrical speech, asymmetrical speech, symmetrical non-speech, and asymmetrical non-speech stimuli, respectively. These measures are within the expected range of values, and the degree of difference in level measured in each stimulus condition has been shown to not affect gap detection in past research.

2.4 Procedure

Each listener participated in two testing sessions which ranged from 1.5 to 2.5 hours in length. Approximately 4 to 5 hours total testing time was required of each participant. Air-conduction pure-tone thresholds, speech recognition thresholds, and word discrimination scores were first obtained for each participant to determine candidacy for the experimental testing and to obtain specific information on listeners' audiometric hearing levels (see Appendix B and Appendix C for audiometric thresholds and other participant characteristics). If hearing levels met the criteria for participation, the participant then filled out a Hearing and Language History questionnaire, and the Mill Hill vocabulary test (Raven, 1938) before proceeding with the experimental gap-detection test procedures.

2.4.1 Apparatus and Physical Setting

All testing was carried out in a double-walled sound-attenuating IAC booth. The presentation of the auditory stimuli for the gap detection task was controlled by the experimenter in a separate sound-attenuating testing room adjacent to the sound-attenuating booth. Stimuli were digitally stored on a computer hard drive, and presentation was controlled using Matlab 6.0.0.42a software. The gap detection stimuli were routed from the computer via USB connection to Tucker Davis Technologies (TDT) System III modules which include the RP2.1 real-time processor and HB7 headphone driver. The HB7 attenuation dial was set to –24 dB to achieve the desired presentation sound level (see calibration details in section 2.3.2). From the TDT HB7 headphone driver, the gap detection sound stimuli, now converted to analog, were presented to the participant binaurally through Sennheiser HD-265 headphones.

From the TDT RP2.1 real-time processor, a four-button, four-light response box was also routed into the sound-attenuated booth and placed on a table directly in front of the participant. The middle two lights and buttons were covered. A light on the left side of the response box was visible with a corresponding button underneath it, and a light on the right side was visible with a corresponding button underneath it. As gap detection stimuli were presented in pairs, the light on the left would shine simultaneously with the presentation of the first sound, and the light on the right side would shine when the second stimulus in the pair was presented.

The TDT RP2.1 module presented a light display which corresponded to the response box light and button activation. This display indicated the presentation of gap stimuli and the correct and incorrect responses of the participant such that they were visible to the experimenter throughout the testing period. Responses were routed from the response box, through the TDT system, back to the computer via USB connections where the Matlab software stored all data in files specific to each participant for each experimental run.

2.4.2 Experimental Design

The experimental design is detailed in Table 1. All participants completed all eight conditions. Each of the eight younger and each of the eight older participants was assigned in random order to one of eight sequences of presentation of stimulus conditions so that each sequence was performed by one of the members of each age group. The sequences were counterbalanced in regards to each of the three dichotomous stimulus characteristics (long versus short marker duration, speech versus non-speech, spectral symmetry versus asymmetry of markers) to control for overall learning or fatigue effects that might occur throughout testing, or specific interactions between adjacent stimulus conditions.

Half of the younger and half of the older participants completed the long duration marker conditions in the first session and the short duration marker conditions in the second session, while the other half performed the testing in the opposite order with respect to marker duration. Within each of the two sessions, the order of speech versus non-speech and symmetrical versus asymmetrical markers conditions were counterbalanced between participants such that each condition was tested once in each sequence position (see Table 1).

Table 1. Order of presentation of stimulus conditions for participants in each age group.

Partici-pant in Each Age Group	Long				Short			
	Speech		Non-speech		Speech		Non-speech	
	S*	A**	S	A	S	A	S	A
1	3	1	4	2	7	5	8	6
2	4	2	3	1	8	6	7	5
3	1	3	2	4	5	7	6	8
4	2	4	1	3	6	8	5	7
5	6	5	8	7	2	1	4	3
6	8	7	6	5	4	3	2	1
7	5	6	7	8	1	2	3	4
8	7	8	5	6	3	4	1	2

* S=Symmetrical
** A=Asymmetrical

2.4.3 Testing Protocol

If hearing levels were sufficient for participation (see Section 2.2 for audiometric criteria), the listener was then given initial instructions for the gap detection task. Refer to Appendix E for specific instructions. The initial stimulus condition for each participant depended on the order of presentation as determined by the experimental design outlined in Section 2.4.2. For example, as indicated in Table 1, the first participant (Subject 1) in both age groups first heard a non-speech stimuli with long duration and asymmetrical markers. Following the first portion of instructions, a practice run of relatively easy gap detection stimuli was presented. Instruction proceeded only when six consecutive correct responses were recorded for the first practice run. If the listener had difficulty producing six consecutive correct responses, further instruction and practice was provided until this was achieved. Following six consecutive correct responses, the second portion of instructions was provided, after which an additional practice run was presented in which the gap size was varied such that the gap detection task was more unpredictable and difficult. Six consecutive correct responses were again required for this second practice run before the participant began the initial non-practice experimental run. A practice procedure was repeated each time the stimulus condition was changed in order to ensure proper orientation to the unique characteristics of each of the eight stimulus types.

The gap detection threshold is defined as the smallest silent interval that a listener can detect in a sound stimulus. A two-interval, two-alternative, forced-choice paradigm, following Schneider and Hamstra (1999), was used to determine gap detection thresholds for each listener in each condition. Specifically, during each trial, there were two stimulus intervals; one stimulus containing a silent gap and the other stimulus being a continuous sound with no silent interval. The stimulus with the gap randomly occurred either in the first or second interval. The second interval was presented 1 second following the first interval. During the presentation of the stimulus in the first interval, the light above the first button flashed; during the presentation of the stimulus in the second interval, the light above the second interval flashed. The task of the participant was to indicate which of the two sounds contained the gap stimulus by pressing the button on the response box that corresponded to the chosen interval. Following the participant's response, a brief feedback light flashed above the response button corresponding to the interval which had actually contained the gap.

For the first gap detection trial, the size of the gap in the gap stimulus within the pair depended on the marker symmetry of that condition. For all symmetrical marker stimuli, the initial gap size was set to 66.0 ms. For asymmetrical stimuli, the initial gap size was 350.0 ms. An adaptive 3 down 1 up rule was used to determine the gap size in subsequent trials. The duration of the gap was decreased by following three correct responses, and increased following one incorrect response. Initial step sizes were 16.0 ms for symmetrical stimuli and 32.0 ms for asymmetrical stimuli. The step sizes changed with each reversal by a factor of one-half, until a minimum resolution limit of 2.0 ms was reached. This staircase procedure was used to determine the 79.7% point on the psychometric function (Levitt, 1971). Each test run was completed after 12 reversals, and the average of the last eight reversals defined the gap-detection threshold for each run. Three runs were conducted in each of the eight stimulus conditions for all listeners. Gap detection thresholds in each condition were calculated as the mean threshold from the three runs.

After the completion of three runs in the first stimulus condition, the next condition was introduced with a practice session as described above. In this way, testing was completed for the first four conditions in the first session and the last four conditions in the second session. Thus, 12 runs were completed during each session, for a total of 24 experimental runs per participant.

Participants were advised that they had the opportunity after any run to take a break if they were fatigued, and they were encouraged to take a short break after each three-run condition was completed. Refreshments were provided for participants.

3. RESULTS

3.1 Overview

The results of this study will be presented in the following sections. An overview of the main effects of the between-subjects experimental variable (age group) and within-subjects experimental variables (stimulus symmetry, type, and duration) on gap detection threshold scores are presented, followed by a preliminary description of the interactions that were observed between these variables. Raw experimental data for each participant is included in Appendix F.

3.2 Results in Each Stimulus Condition for Younger and Older Adults

Figure 1 and Figure 2 depict gap detection thresholds for younger and older adults in each of the eight experimental conditions. Gap thresholds in symmetrical and asymmetrical stimuli conditions are presented in Figure 1 and Figure 2, respectively. Symmetrical stimuli consistently resulted in much lower gap detection thresholds (mean across all symmetrical conditions = 2.19 ms[4], SD = 1.15 ms) in comparison to scores obtained in asymmetrical conditions (mean across all asymmetrical conditions = 49.94 ms, SD = 54.88); therefore, it is convenient to plot the results in the symmetrical and asymmetrical conditions separately.

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[4] Strictly speaking, "gap" detection thresholds cannot be directly measured in the same way when the peaks of the leading and lagging stimuli are within 4 ms as can be done when they are separated to a greater extent. Below a separation of 4 ms, rather than a gap there is an attenuated gap in which there is a dip in energy rather than an interruption. A more accurate way to describe thresholds in this region has yet to be agreed upon (personal communication, Stan Hamstra, 2002).

Figure 1. Gap detection thresholds (mean and standard error) for symmetrical speech and non-speech stimuli with short and long marker durations for younger and older listeners.

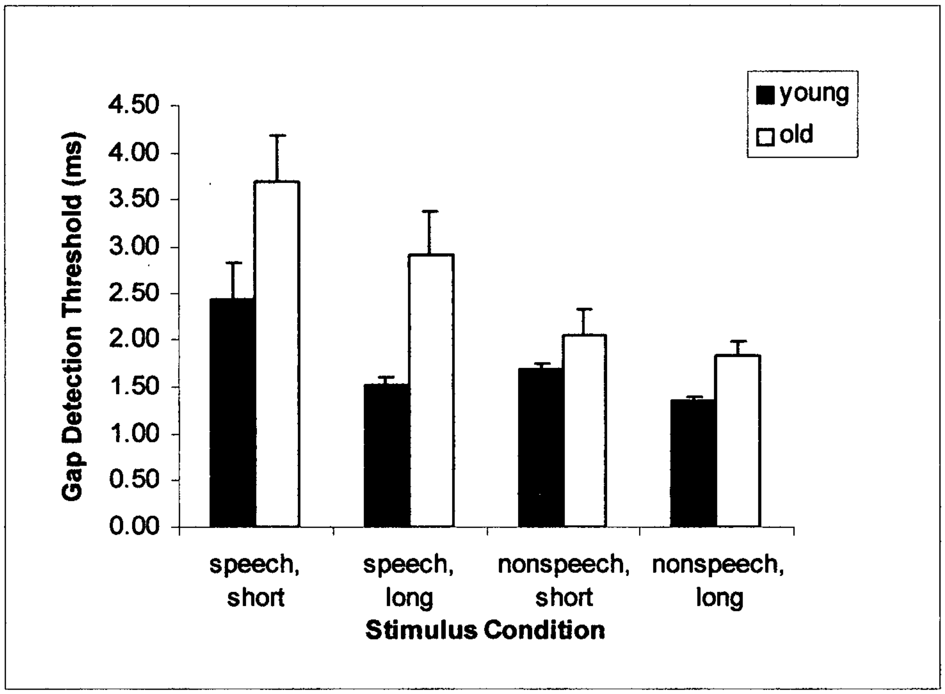
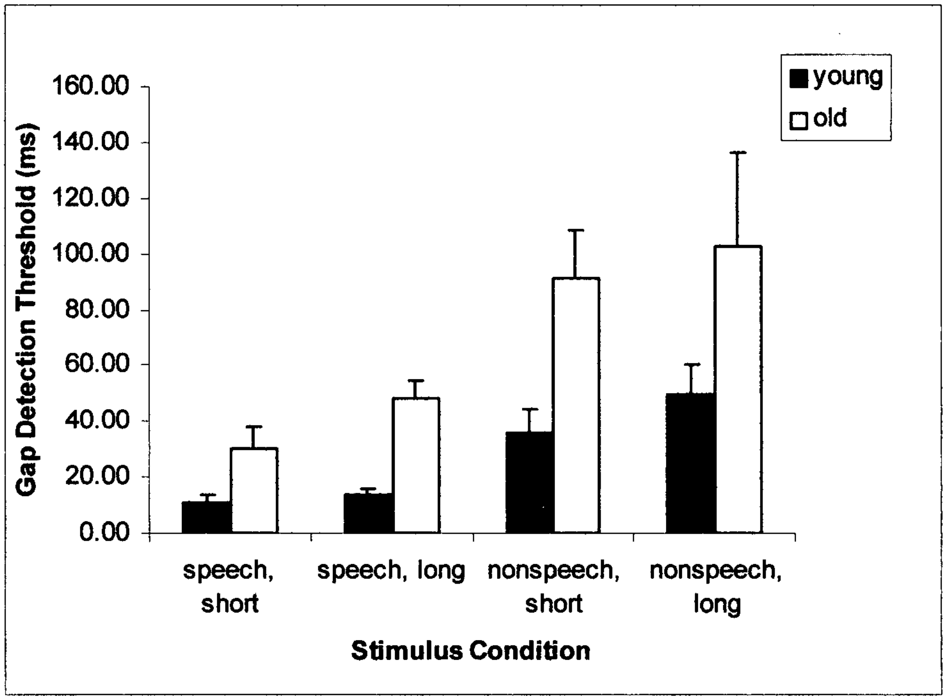


Figure 2. Gap detection thresholds (mean and standard error) for asymmetrical speech and non-speech stimuli with short and long marker durations for younger and older listeners.



3.3 Main Effects

The main effects shown in Figures 1 and 2 are described in this section. An analysis of variance (ANOVA), with age group as a between-subjects factor and symmetry, type, and duration as within-subjects factors, was carried out to test the significance of all main effects.

3.3.1 Effect of Age Group

The average gap detection thresholds of younger adults are better than those of older adults in all conditions, as is evident in Figures 1 and 2. Averaging across all conditions, the gap detection threshold for the older group was 37.53 ms (SD = 58.54 ms) and for the younger group it was 14.60 ms (SD = 21.85 ms). The ANOVA confirmed that there was a significant main effect of age, $F(1,14) = 11.690$, $p < 0.005$.

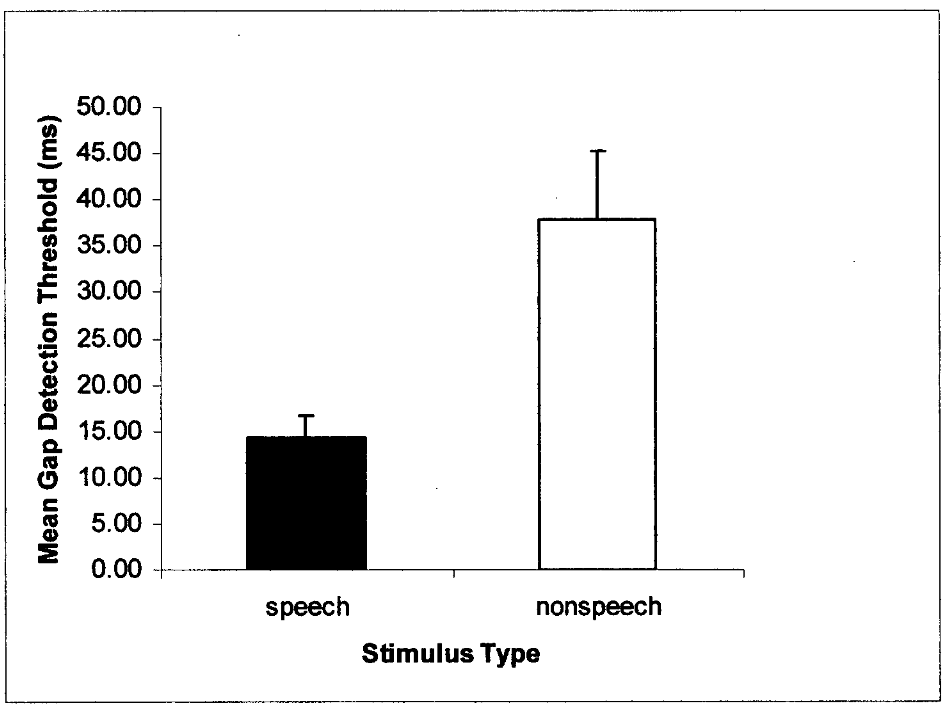
3.3.2 Effect of Spectral Symmetry

As clearly shown in a comparison of gap detection scores in Figure 1 compared to those in Figure 2, listeners performed better when the spectral content of the leading and lagging markers were symmetrical than when they were not symmetrical. In asymmetrical conditions, the mean gap detection threshold was 49.94 ms (SD = 54.88), whereas in symmetrical conditions it was 2.19 ms, (SD = 1.15 ms). The ANOVA confirmed that there was a significant main effect of symmetry on gap thresholds, $F(1, 14) = 53.150$, $p < 0.0005$.

3.3.3 Effect of Stimulus Type (Speech versus Non-speech)

As shown in Figure 1 (symmetrical conditions), gap detection thresholds are larger for speech than for non-speech stimuli; however, this pattern is reversed in Figure 2 (asymmetrical conditions) where gap detection thresholds are larger for non-speech than for speech stimuli. Averaging over all conditions (both asymmetrical and symmetrical), the mean gap threshold is larger for non-speech (Mean = 37.92 ms, SD = 59.42 ms) than for speech stimuli (Mean = 14.21 ms, SD = 18.86 ms), as shown in Figure 3. It should be noted that in considering the overall effect of stimulus type, the large gap detection thresholds obtained in the asymmetrical conditions dominate those obtained in symmetrical stimuli conditions (see description of interaction effect in 3.4 below). The ANOVA confirmed a significant main effect of stimulus type, $\underline{F}(1,14) = 26.078$, $\underline{p} < 0.0005$.

Figure 3. Gap detection thresholds (mean and standard error) as a function of stimulus type.



3.3.4 Effect of Duration

Gap detection thresholds were larger for stimuli with long (250 ms) duration markers (Mean = 30.90, SD = 54.92), than for stimuli with short (40 ms) duration markers (Mean = 21.26, SD = 33.28). The ANOVA confirmed a significant main effect of marker duration, $F(1,14) = 5.752$, $p < 0.05$, even though the main effect of stimulus marker duration was not included in the current scientific hypotheses

3.4 Interaction Effects

In addition to the main effects described above, significant interactions with spectral symmetry were also observed as described below.

3.4.1 Age Interactions

It was predicted that, at least in some stimulus conditions, older adults would obtain gap detection thresholds significantly larger than those of younger adults, with age effects being most likely to be observed when marker duration is short. However, no significant interaction between age and marker duration was observed. The ANOVA did not provide evidence to support the expected age group x marker duration interaction, $F(1,14) = 2.112$, $p = 0.168$. Furthermore, the prediction that an age-dependent duration effect would depend on stimulus symmetry was not confirmed, as there was not a significant three-way age group x duration x symmetry interaction, $F(1,14) = 2.059$, $p = 0.173$.

An interaction of age x stimulus type (speech versus non-speech) was not indicated in the ANOVA, $F(1,14) = 2.497$, $p = 0.138$. A predicted outcome of this interaction was not formulated in the hypothesis.

3.4.2 Interactions with Spectral Symmetry

The spectral symmetry of the stimuli interacted with other factors. As depicted in Figures 1 and 2, age differences were apparent in spectrally asymmetrical but not in spectrally symmetrical conditions. This observation was confirmed by the ANOVA with a significant interaction between symmetry and age group, $F(1, 14) = 11.329$, $p = 0.005$. A Student-Newman-Keuls (SNK) test of multiple comparisons confirmed that in asymmetrical conditions (differing spectral content of leading and lagging markers), but not in symmetrical conditions (equal spectral content of markers), the gap detection thresholds of older adults were significantly larger than those of younger adults, $p = 0.05$. This interaction is depicted in Figure 4 which shows the mean gap detection thresholds and standard deviations for each age group in both spectrally symmetrical and asymmetrical conditions (see also Table 2).

Figure 4. Gap detection thresholds (mean and standard error) as a function of stimulus symmetry for younger and older listeners.

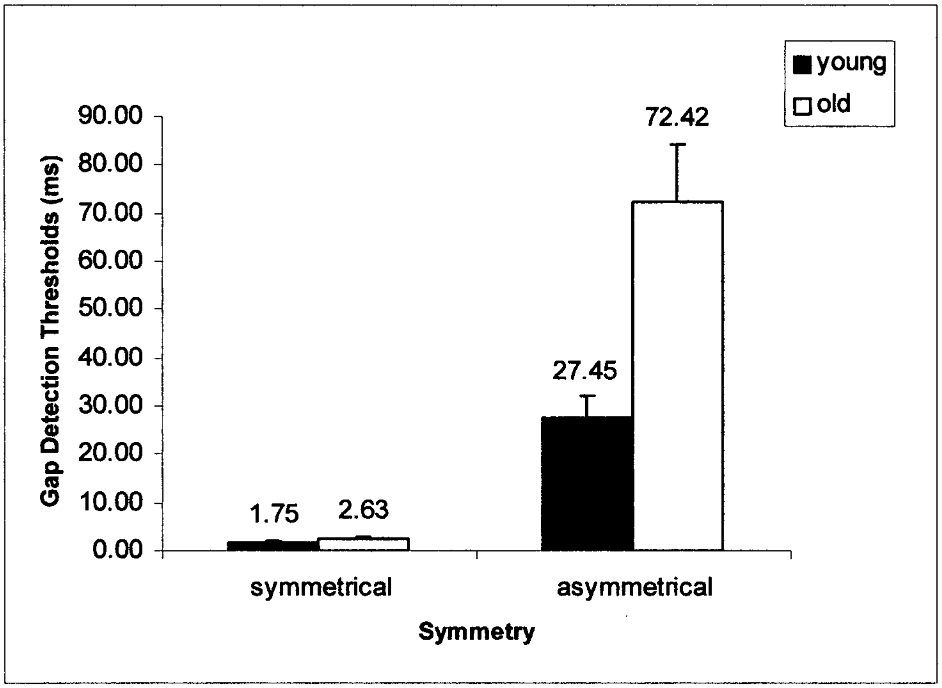
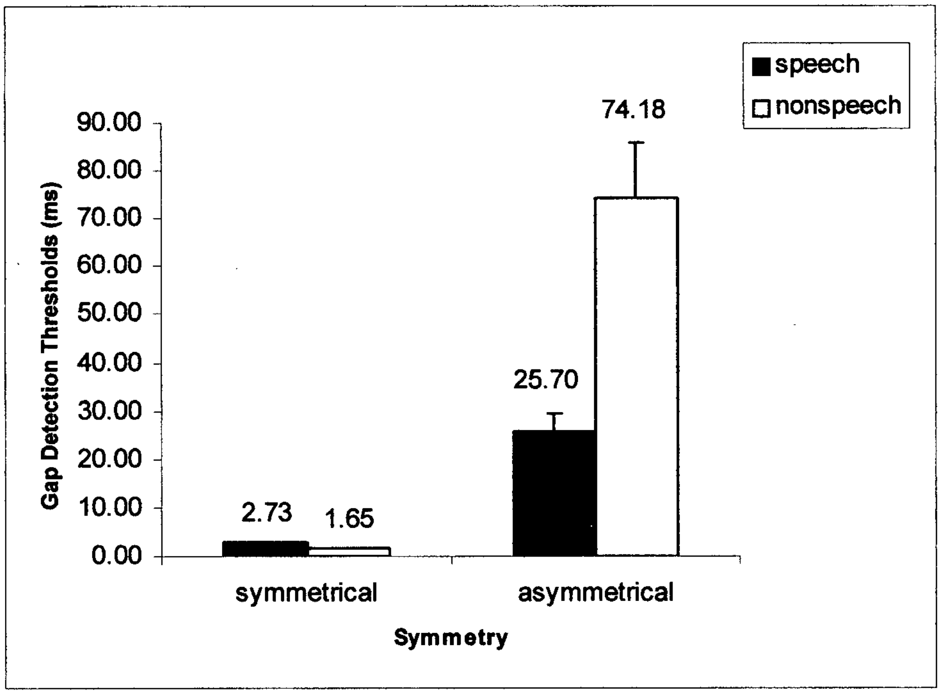


Table 2. Spectral symmetry by age group interactions

Age Group	Symmetry	Gap Detection Threshold (ms)	
		Mean	Standard Deviation
Young Adults	Symmetrical	1.75	0.82
	Asymmetrical	27.45	25.06
Old Adults	Symmetrical	2.63	1.24
	Asymmetrical	72.42	66.71

In Figure 1 it is evident that gap detection thresholds tend to be larger for speech stimuli than for non-speech stimuli in the symmetrical conditions. The opposite is true in the asymmetrical conditions (Figure 2), in which speech stimuli are associated with smaller gap detection thresholds compared to non-speech stimuli. The interaction between stimulus symmetry and type is depicted in Figure 5. Mean gap detection thresholds and standard deviation measures for the four combinations of spectral symmetry and speech versus non-speech stimulus type are provided in Table 3. The ANOVA also confirmed that there was a significant interaction between spectral symmetry and stimulus type (speech versus non-speech), F(1,14) = 26.583, p < .0005. A Student-Newman-Keuls test of multiple comparisons confirmed that in the spectrally asymmetrical conditions, but not in the spectrally symmetrical conditions, gap detection thresholds were significantly larger for non-speech than for speech stimuli, p = 0.05. The tendency for gap detection thresholds to be larger for speech stimuli compared to non-speech stimuli in symmetrical conditions was not found to be significant.[5]

Figure 5. Gap detection thresholds (mean and standard error) as a function of stimulus symmetry and stimulus type.



[5] In order to investigate the possible influence of differing variance measures in asymmetrical versus symmetrical conditions on the test of significant interaction between symmetry and stimulus type, the raw data from all subjects was transformed to a log scale and analyses were repeated. Indeed, when variance measures were more closely equated through this statistical manipulation, a Student-Newman-Keuls test of multiple comparisons determined that speech stimuli are associated with significantly higher gap detection thresholds compared to non-speech stimuli in the symmetrical conditions (see Figure 1). This manipulation was carried out for all statistical analyses, and no other novel significant effects were found.

Table 3. Spectral symmetry by stimulus type interactions

Spectral Symmetry	Stimulus Type	Mean Gap Detection (ms)	
		Mean	Standard Deviation
Symmetrical	Speech	2.73	1.35
	Non-speech	1.65	0.55
Asymmetrical	Speech	25.70	21.18
	Non-speech	74.18	66.78

An additional interaction, which was not included in the current hypotheses, was found between marker symmetry and marker duration. The ANOVA indicated that there was a significant interaction between spectral symmetry and marker duration (short versus long), $F(1,14) = 6.383$, $p < .05$. A Student-Newman-Keuls test of multiple comparisons confirmed that gap detection thresholds were significantly larger for long duration markers than for short duration markers in the spectrally asymmetrical conditions, but not in the spectrally symmetrical conditions, $p = 0.05$.

4. DISCUSSION

4.1 Introduction

The main purpose of the present study was to determine if older adults with normal hearing in the speech range differ from younger adults in their ability to detect gaps introduced between markers differing in symmetry of frequency content. This included an investigation into whether there is an age-related difference in performance between real speech stimuli and non-speech stimuli which embody speech-like temporal and spectral characteristics. Additional signal characteristics were varied in testing to replicate and compare to past research results which utilised markers of symmetrical frequency and varied duration.

In this section, the results which addressed the effects of age and stimulus characteristics (marker symmetry, speech vs. non-speech, and marker duration) in Section 3 will be discussed in terms of their relation to the hypotheses stated in Section 1.8. The primary research goal of this study was to investigate age-related differences in gap detection performance in these conditions. A large main effect of age was found, with the overall mean gap detection threshold for older adults (37.53 ms) being significantly larger than the mean gap detection threshold for younger adults (14.60 ms). These results indicate that null hypothesis #5, which states that older adults with normal audiometric thresholds in the speech range will have gap detection thresholds which do not significantly differ from those of younger adults, can be rejected, and the predicted main effect of age is confirmed as being true. Interactions between age and other stimulus variables were of interest as well (See hypotheses in Section 1.8). The results did indicate an interaction between age and marker symmetry, as will be discussed in

Section 4.5, but other age interactions were not shown to be significant. Findings and issues related to these age interactions will be described in detail in the following sections.

4.2 Gap Detection with Symmetrical versus Asymmetrical Markers

The results of this study support the rejection of Null Hypothesis #1, which states that gap detection ability measured with leading and lagging markers of equal frequency will not significantly differ from gap detection ability measured when leading and lagging markers are of different frequency composition. Older and younger listeners were tested in symmetrical and asymmetrical marker conditions, and as predicted, results (see Section 3.3.2) indicated that participants consistently performed better in conditions with markers of equal frequency. As stated in the results section, the largest mean gap threshold for either age group, in any of the four symmetrical conditions was 3.71 ms, approximately one-third of the lowest mean gap detection threshold, 11.09 ms, obtained in any of the four asymmetrical stimulus conditions for either age group. This finding is in agreement with past studies which have found a similar effect of reduced performance when listeners detect a gap between markers of differing frequency, compared to equal frequency (e.g., Fitzgibbons et al., 1974; Formby et al., 1993; Phillips et al., 1997).

The mean overall gap detection thresholds in the symmetrical conditions was 2.19 ms, which is comparable to within-channel results found in other studies when similar marker durations were used (e.g., Schneider & Hamstra, 1999). The overall mean gap detection threshold in asymmetrical conditions was 49.94 ms, over 20 times the length of the mean symmetrical gap thresholds. For the younger group only, the mean gap detection threshold in asymmetrical conditions was 27.45, about 10 times the length of the mean symmetrical gap thresholds. The overall mean difference is larger than found in past studies, but the mean for younger listeners is in agreement with previous work conducted with younger adults (see Section 4.5 for a detailed discussion of the interaction between age and symmetry). For example, Phillips et al. (1997) found that in a between-channel condition of maximal frequency discrepancy between noise bursts (separated by two octaves), gap thresholds were three to ten times worse compared to within-channel performance. To our knowledge, no previous study has used exactly the same type of asymmetry as was used in the present study.

The robust symmetry effect in the current study lends support to the hypothesis that the underlying perceptual mechanism involved in the detection of a gaps between sounds of differing spectral content is, at least partially, distinct from that involved in within-channel gap detection, and does not conflict with the prevalent description of this mechanism involving a timing operation across activity in different perceptual channels (Phillips et al., 1997). The fact that between-channel thresholds were particularly high may reflect the increased susceptibility of this between-channel operation, but not within-channel processing, to some of the additional factors varied, including age, type, and marker duration. Indications of such interactions in the results will be addressed further as they arise in the following sections.

4.3 Gap Detection with Speech versus Non-Speech Stimuli

Null hypothesis #2, which states that gap detection thresholds measured with natural speech stimuli will not differ from those measured in non-speech conditions, was rejected in this study. Results outlined in Section 3.3.3 indicate that overall, speech stimuli produced better performance, indicated by a lower mean gap detection threshold (14.21 ms) compared to non-speech conditions (37.92 ms). In discussing this main effect of type (speech vs. non-speech), however, it is important to note the significant interaction between type and symmetry (see Section 3.4.2). A review of Figure 1 and Figure 2 reveals that speech stimuli were associated with improved gap detection performance only when the stimulus markers differed in the symmetry of frequency content, and the general trend in the symmetrical conditions was in the opposite direction (see footnote in Section 3.4.2 for statistical investigation of this trend). The post-hoc analysis determined that, in fact, the speech versus non-speech type effect was only significant in the asymmetrical conditions. Thus, our results indicate that when two successive sound signals are modelled to approximate the spectral and temporal configuration of phonemically important consonant-vowel combinations, the use of natural speech markers benefits listeners in their ability to resolve a silent interval located between them, relative to performance with computer-generated markers which have similar duration, energy and overall spectral content. No such advantage is observed when the markers are symmetrical.

The findings outlined above raise a question concerning what characteristics of the non-speech stimuli challenge temporal processing, or conversely, what is inherent in real speech which supports temporal processing. One possibility is that the improved performance in the speech conditions is partly due to some overlapping spectral content between the leading [s] marker, and the lagging [u] marker that was not present in the non-speech stimuli (see Appendix D for time waveforms and spectrograms of asymmetrical speech and non-speech stimuli). Past research indicates that in conditions of spectral dissimilarity between markers with a degree of overlap, gap detection thresholds still follow between-channel patterns. For example, Grose et al. (2001) found that between-channel gap thresholds are elevated even in conditions when a narrow-band marker falls within the spectral range of a wide-band marker (see Section 1.7.3). It has also been suggested by Phillips (1999) that in any condition in which markers activate more than one perceptual channel, both within- and between-channel processes may be activated, and the further apart the stimuli are along the relevant stimulus dimension (spectral content in this case), the more likely the perceptual operation is to rely on between-channel processes, thus reducing overall performance.

An additional hypothesis that may explain why gap thresholds are improved in natural speech conditions may involve the auditory system's ability to take advantage of the cross-band correlations provided by the harmonic structure of speech sounds (e.g., Greenberg, 1996). Therefore, an important difference between the speech and non-speech stimuli in this study is the synchrony cues provided by the concentration of energy found at harmonics of the fundamental frequency in the lagging [u] marker. The importance of synchronicity is suggested by the claim of Shailer and Moore (1987) who found that gaps are easier to detect when the phase is preserved across the gap between the leading and lagging marker, a finding that they attributed to the ringing of the auditory filter which is presumed to continue throughout the gap.

It is noteworthy that there was a trend for the older listeners to perform worse than the younger listeners in the non-speech conditions and the difference in performance of the age groups was less in the speech conditions; however, there was not a significant interaction of age x speech versus non-speech stimulus type.

4.4 Gap Detection with Short versus Long Markers

The results of this study did not show an overall main effect of stimulus marker duration, thus accepting null hypothesis #3, contrary to the predicted outcome. In addition, null hypothesis #4 is rendered moot, as it was formulated based on a rejection of null hypothesis #3. As stated in the research hypothesis accompanying null hypothesis #4 (see Section 1.8), it was expected that there would only be an effect of age on gap detection thresholds in symmetrical conditions for short marker durations but no such interaction with age was observed in the present study (see Section 4.6 for a discussion of the interaction between marker duration and symmetry condition). This prediction followed the results of Schneider & Hamstra (1999), who found an age x duration interaction using symmetrical 2000-Hz tonal gap stimuli. It should be noted that these authors used marker durations ranging from 0.83 ms to 500 ms, with the strongest age differences in gap detection performance being at durations much shorter than those utilised in the current study. Less robust age effects were found by Schneider and Hamstra (1999) at marker durations of 40 ms and 200 ms, the former of which is equivalent to the "short" marker used in the present study, and the latter of which is only 50 ms shorter than "long" marker used in the present study. In fact, the age-related differences in gap detection thresholds found in the present study (0.83 ms for the 40 ms marker and 0.93 ms for the 250 ms marker) correspond closely to the age differences found for the 40 ms and 200 ms marker durations in the study of Schneider and Hamstra (1999; see Figure 3, pg. 375). With the relatively small number of participants included in the current paper (eight in each age group, compared to twenty in the study by Schneider and Hamstra, 1999), it would not be surprising if an interaction between duration and age groups were not found using only 40 ms and 250 ms markers. In other words, the duration values chosen in this study may have been too close in proximity to reveal an age x duration interaction. It was decided not to use a marker shorter than 40 ms or longer than 250 ms because it was important to use a range of marker durations that could possibly be encountered in speech.

4.5 Age-Effect on Gap Detection Ability in Asymmetrical Conditions

In addition to the confirmation of a main effect of age on overall gap detection thresholds, allowing the predicted rejection of null hypothesis #5, an investigation of an age interaction is presented in null hypothesis #6 which states that the older, normal-hearing adults will have gap detection thresholds in the asymmetrical marker conditions that do not differ from those of younger adults. This null hypothesis was rejected, and the main experimental prediction of this thesis that older adults would have significantly worse thresholds than younger adults in asymmetrical conditions was found to be true. The reasoning behind this research prediction follows from findings which indicate that (1) older adults have decreased speech perception (e.g., CHABA, 1988; Pichora-Fuller, 1997; see Section 1.2), (2) the fact that between-channel stimuli better approximate the spectral configuration of phonemic speech distinctions which rely on the perception of small periods of reduced amplitude (see Section 1.6.2), (3) the indication that between-channel gap thresholds approximate VOT boundaries in spoken language (Phillips et al., 1997; see Section 1.7.1.1) , and (4) the finding that adults have a reduced ability in utilising gaps to distinguish phonemes (e.g., Haubert, 1999; Strouse et al., 1998).

The evidence of a significantly greater age effect in asymmetrical as compared to symmetrical marker conditions, consistent with the findings of many previous studies that did not themselves directly test for this interaction, now prompts questions regarding the basis for the strong finding. It may be that aging differentially affects the types of auditory processing underpinning within-channel vs. between-channel gap detection. Other non-auditory factors such as memory, pattern perception, and attention may also be implicated as discussed below in Section 4.7.

An age x stimulus type interaction was not found, as there was not a tendency for either age group to be more greatly influenced by the effect of speech versus non-speech conditions. This confirms null hypothesis #7, for which there was not an accompanying research prediction.

4.6 Effect of Marker Duration on Gap Detection Ability in Asymmetrical Conditions

An interaction between marker duration and symmetry was indicated in the results (see Section 3.4.2), despite it's exclusion from the current hypothesis. In past research, duration effects using within-channel gap stimuli have been attributed to adaptation (e.g., Schneider & Hamstra, 1999), and an extension of this model seemed unlikely to extend to between-channel stimuli. An explanation of the influence of marker duration on neural adaptation, and the resultant impact on gap detection performance (see Section 1.5.5), is based on the activation of a common neural set for the leading and lagging markers. This model predicts that a reduction in marker duration is associated with reduced recovery from adaptation, and poorer gap thresholds. In asymmetrical stimuli conditions, for which an effect of duration was found in this study, differing channels, and presumably, neural sets are activated by each marker, and an adaptation effect would not account for effects of marker duration. Interestingly, the direction of the duration effect in asymmetrical conditions in this study was opposite of that found in within-channel conditions in past studies (e.g., Schneider & Hamstra, 1999). In asymmetrical conditions, subjects performed significantly worse when the markers duration was long (250 ms) than when is was short (40 ms). To date, at least one other study has found a similar effect of duration in between-channel conditions (Grose et al., 2002), but the mechanisms which underlie this effect are still unclear. Such findings warrant further study into the complexities of temporal processing with between-channel stimuli, and specifically, the time course of between-band analysis.

4.7 General Discussion and Implications

Perhaps the most exceptional finding in the present study was the great difficulty posed in the non-speech, asymmetrical, long-duration condition, primarily for older listeners. In addition to markedly higher mean gap threshold in this condition for older adults (128.67 ms), in several instances an extended period of training was required for older listeners to correctly identify the gap stimulus for six consecutive trials with a large gap size presented (350 ms). For example, participant O-4 (see Appendix B, C and F for participant characteristics and raw data) was able to understand and meet the training criterion (see Section 2.4.3 for practice methods) with relative ease in all conditions except the non-speech, asymmetrical, long-duration stimulus condition. It was necessary for this participant to repeat practice trials several times before he was able to perform the task to criterion, and upon passing the criterion, he obtained a gap detection threshold (308.88 ms) only slightly smaller than the initial, maximal gap size. It seemed that performing this task required a noticeably greater amount of concentration and effort relative to that required in other conditions. Interestingly, participant O-4 was able to perform the short-duration condition with asymmetrical, non-speech stimuli with little difficulty, obtaining a gap threshold of 26.50 ms (see Section 4.6 for a review of the duration x symmetry interaction). In a study of gap duration discrimination in listeners with cochlear hearing loss, Grose et al. (2002) also found that a number of listeners had particular difficulty in between-channel conditions such that they reached the upper limit of gap size, although the age of these participants was not reported. It has been firmly established that gap detection using non-speech, between-channel markers is substantially more difficult compared to within-channel gap detection (e.g., Fitzgibbons, 1974; Pichora-Fuller et al., 1994), but it is not clear why this difficulty may be compounded for older adults as seen in the present study.

The poor performance for older adults in between-channel conditions cannot be attributed to a lack of understanding of the task, since the task is essentially identical in other conditions that do not result in such large gap detection thresholds. In addition, the older participants have normal audiometric thresholds in the speech range, thus discounting any explanation for reduced performance involving poor audiometric acuity.

In recent literature, there has been a transition from using within-channel gap stimuli to between-channel stimuli to measure temporal processing, largely because the latter better approximates the real temporal patterns of speech. Models of the auditory processing involved in between-channel gap detection have implicated a greater degree of central involvement to account for the timing operations which are performed on activated auditory channels which do not in interact at a peripheral level. The temporal resolution deficit seen in older adults in the current asymmetric, speech-like conditions likely reflects a processing deficit involving the interactions between neural channels at a relatively central level. Cognitive and/or attentional factors may also play a critical role in this particularly challenging condition.

Based on within-channel stimuli, some researchers have suggested that the gap detection task is relatively easy to learn, gives stable results, and requires little cognitive processing (e.g., Moore et al., 1992). This may be generally true in within-channel conditions, but research has shown greater variability in between-channel gap detection performance (e.g., Philips, 1997), and as was evident in the present research, a greater deal of practice is required when using between-channel stimuli. Furthermore, these findings, and the modelling of more central auditory mechanisms in between-channel processing, suggest that the relationship between cognitive performance and gap detection may be significant when listeners resolve a temporal cue between sounds differing in frequency content. Other researchers have suggested that temporal judgements made in tasks of increased complexity may rely to a greater extent on cognitive processing rather than sensory processing (e.g., Moore, 1992; Wingfield, 1985).

Another possibility is that the declines in performance associated with aging in the long-duration, asymmetrical, non-speech conditions is related to memory processes as opposed to temporal processing difficulties alone. Over the course of a trial, the listener must attend to the stimulus presented first, and after a one second inter-stimulus delay, attend to the second stimuli, after which a decision process must be executed in order to determine which of the two stimuli had a gap. The one second inter-stimulus interval is relatively large compared to that used in other gap detection studies, adding to the potential influence of memory processes on performance. In the asymmetric conditions, some older adults may have greater difficulty in holding the time pattern of the stimuli in memory when performing the task. It should be noted, though, that if the commitment of an auditory event to memory is dependent on a minimal required amount of consolidation time, we would expect to see worse performance with shorter duration markers compared to longer duration markers. The opposite effect of duration was found in this study.

The significantly better gap detection performance in speech versus non-speech asymmetrical conditions in older adults may reflect enhanced ability to process the patterns of natural speech signals. An example of this is discussed in Section 4.3, in which it was stated that some researchers have proposed that humans take advantage of the cross-band correlations provided by the harmonic structure of speech sounds (e.g., Greenberg, 1996). It is possible that words, syllables, or other similar patterns in speech are processed as unified objects, and attentional, and memory processes may also interact with this special ability to process speech patterns. It would not be surprising to find that in background noise, or with degraded speech signals, such enhanced processing abilities would be compromised.

Some researchers (e.g., Humes et al., 1994; van Rooij & Plomp, 1992) have proposed that the primary difficulty of older adults in understanding language spoken in everyday conditions results from elevated audiometric thresholds. Proponents of such a view argue that amplification should be the focus of audiologists in treating older adults with hearing difficulties. The current results do not support this view, and suggest that temporal deficits are present in older adults, and likely contribute to their ability to detect phonetically important cues in spoken language. Past studies utilising within-channel gap stimuli as a measure of temporal processing in older adults have found varying degrees of correlation between these measures and a variety of measures of speech perception (e.g., Gordon-Salant & Fitzgibbons, 1993; Strouse et al., 1998; Tyler et al., 1982). Snell and Frisna (2000) found that correlations between word recognition and gap detection thresholds measured in symmetrical conditions were stronger for younger adults than older adults, and concluded that word recognition measures for older adults cannot be explained by variations in gap thresholds as measured in that study. Strouse (1998) also indicated that the stimuli used in her study were not sufficiently representative of real speech. It has been shown that between-channel stimuli more closely approximate phoneme combinations in spoken language, and may tap into crucial cues for distinguishing phonemes (Phillips, 1997). Results from the current study suggests that between-channel processing results in age-related differences greater than those found in within-channel conditions. It would be sensible for further research to explore the relationship between temporal processing of between-channel gap detection thresholds and measures of speech perception in older adults to further explore the nature of the age-related difficulties in auditory processing that underpin their difficulties in speech processing. As the specific mechanisms underlying such processing difficulties are uncovered, diagnostic tools can be developed to quantify these perceptual abilities, engineers can design technology that may be more useful, and rehabilitative professionals can recommend, or supplement amplification with treatment measures that focus on creating optimal auditory environments and improving the relevant aspects of the speech signal through behavioural or technological means.

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APPENDIX A

Informed Consent Form

APPENDIX B

Individual Participant Pure-Tone Thresholds (dB HL)

Participant	Test Ear	Test Frequency (Hz)							
		250	500	1000	2000	3000	4000	6000	8000
Y-1	R	5	-5	0	0	0	0	0	0
	L	0	0	0	-5	0	5	10	5
Y-2	R	-5	-10	-5	-5	-5	-10	-10	-10
	L	0	-10	-10	-5	-5	-5	-5	-10
Y-3	R	5	0	0	10	5	5	5	0
	L	0	-5	-5	5	0	-5	5	5
Y-4	R	0	0	0	0	0	0	15	0
	L	0	10	5	0	0	0	5	0
Y-5	R	-5	0	0	-5	0	0	5	5
	L	-5	-5	-5	-5	-5	-5	5	5
Y-6	R	5	5	5	-5	-5	-5	0	5
	L	5	10	0	10	10	10	10	10
Y-7	R	0	0	0	-5	0	0	5	0
	L	5	5	0	-10	5	5	10	0
Y-8	R	15	10	10	-5	-5	0	5	5
	L	10	5	5	-5	0	5	10	0
O-1	R	5	10	10	20	15	15	15	50
	L	10	10	15	20	10	20	20	45
O-2	R	5	5	10	15	25	30	45	55
	L	0	5	5	20	25	45	60	60
O-3	R	10	10	10	10	5	10	15	20
	L	10	10	10	5	5	5	20	20
O-4	R	15	15	15	20	20	45	35	40
	L	15	10	20	25	20	35	60	55
O-5	R	15	20	25	25	20	15	45	70
	L	20	20	25	20	15	30	50	70
O-6	R	15	15	20	25	25	35	50	55
	L	15	15	15	20	20	30	35	45
O-7	R	10	5	5	0	5	5	25	45
	L	5	0	5	5	10	10	20	55
O-8	R	15	15	15	20	25	30	45	50
	L	10	15	20	15	20	20	45	55

APPENDIX C

Individual Participant Characteristics

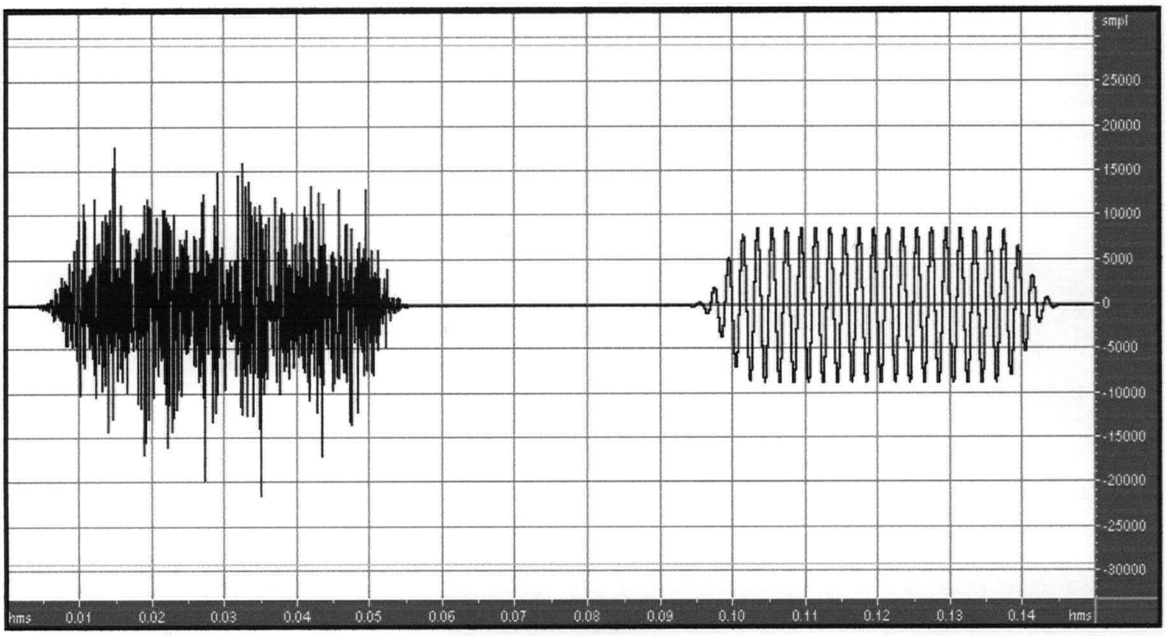
Participant	Pure Tone Average (dB HL)		SRT (dB HL)		Age (Years)	Years of Education
	R	L	R	L		
Y-1	-1.7	-1.7	-5	0	35	16
Y-2	-6.7	-8.3	-5	-5	22	
Y-3	3.3	-1.7	0	0	27	18
Y-4	0	5	0	5	24	18
Y-5	-1.7	-5	0	0	28	19
Y-6	-1.7	6.7	5	0	26	21
Y-7	-1.7	-1.7	0	5	21	15
Y-8	5	1.7	5	5	25	18.5
O-1	13.3	15	10	5	81	16
O-2	10	10	10	15	71	20
O-3	10	8.3	10	10	72	12
O-4	16.7	18.3	10	15	81	17
O-5	23.3	21.7	20	20	71	21
O-6	20	23.3	15	15	75	12
O-7	3.3	3.3	5	5	74	12
O-8	16.7	16.7	15	15	81	15

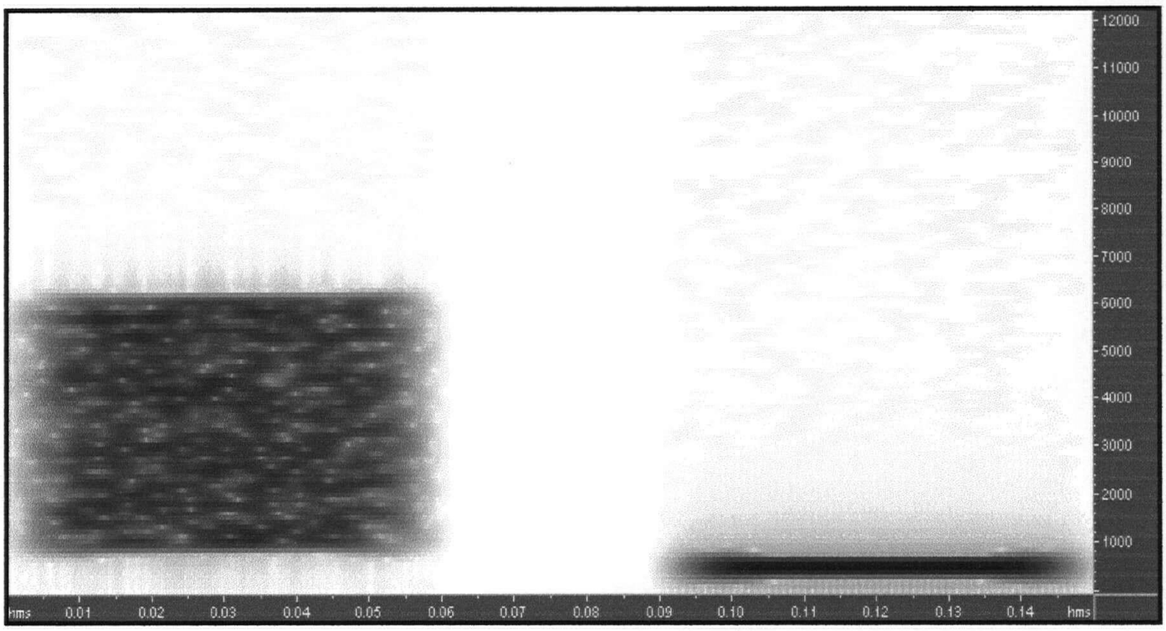
APPENDIX D

Time Waveforms and Spectrograms of Stimuli

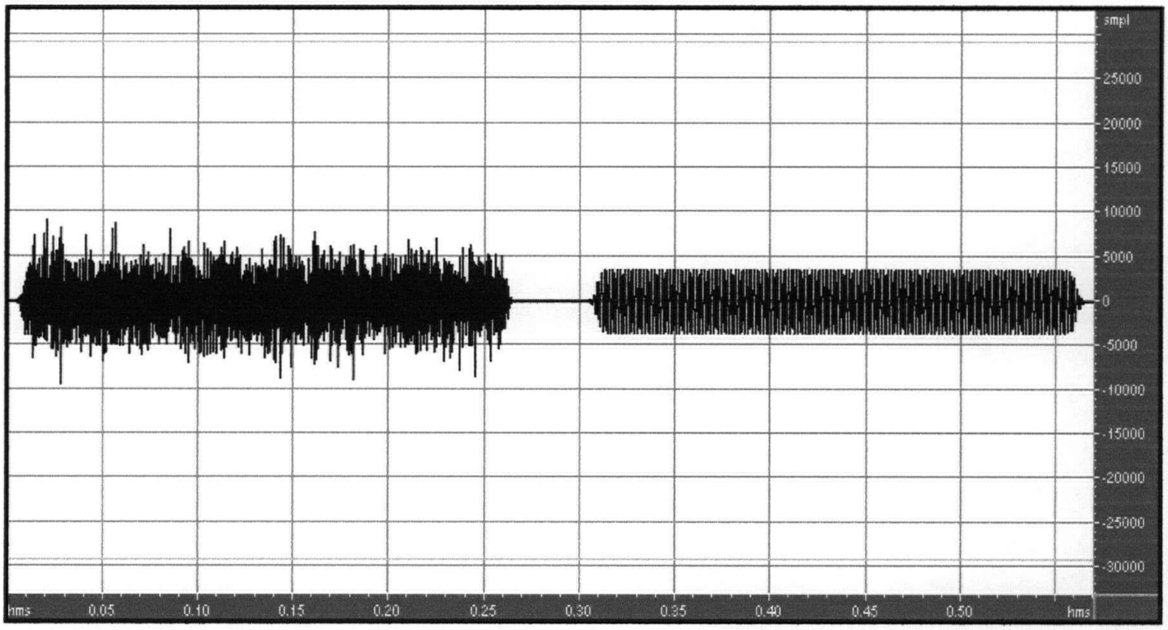
All of the following examples from each of the eight stimulus conditions include a 50 ms gap between leading and lagging markers.

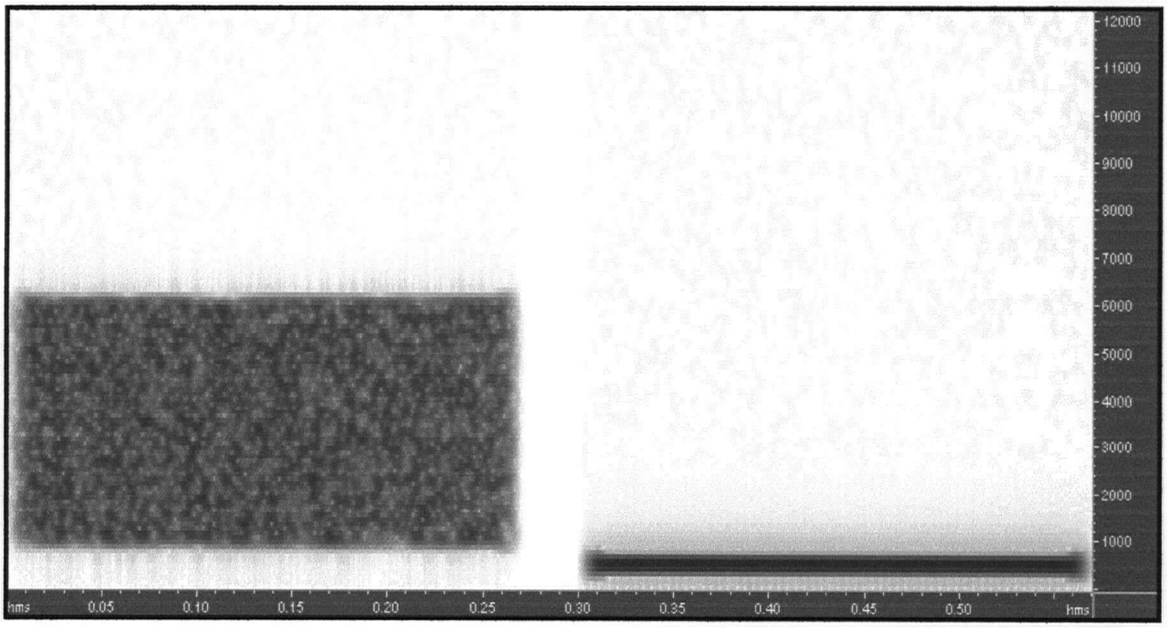
<u>Stimulus Condition 1</u> Type: Non-Speech,
Marker Duration: Short
Symmetry: Asymmetrical



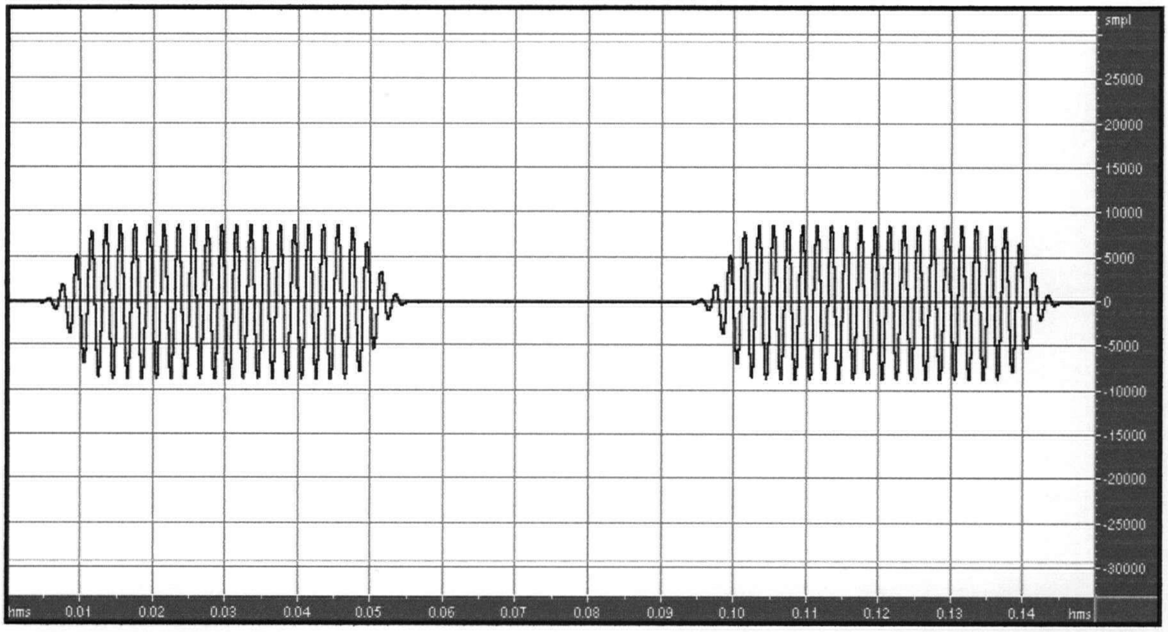


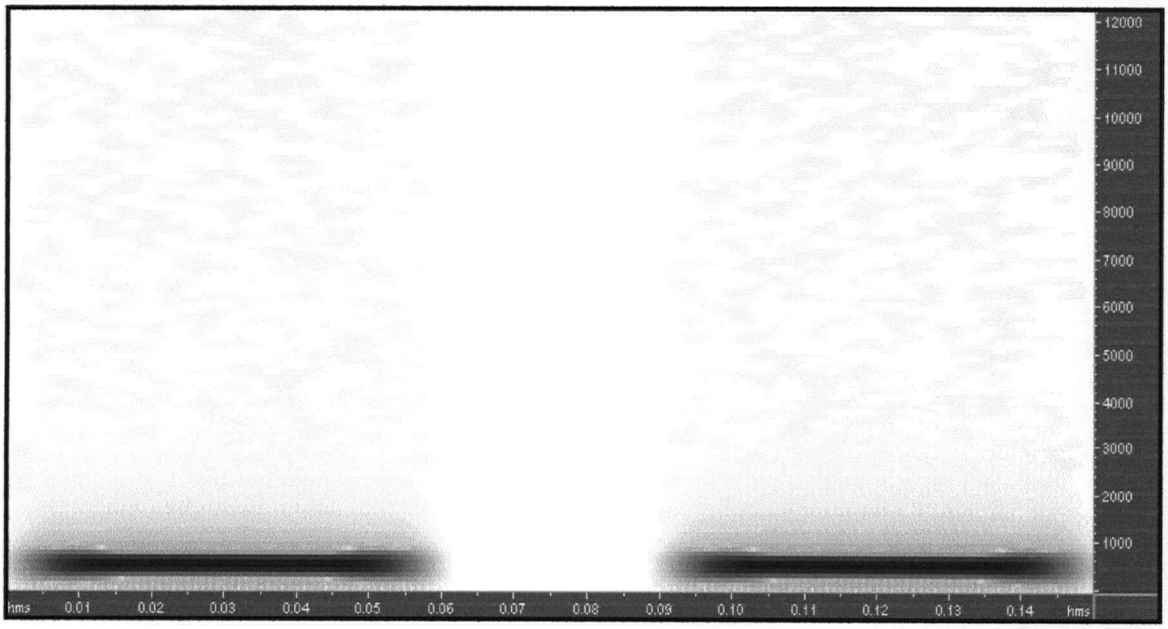
Stimulus Condition 2 Type: Non-Speech,
Marker Duration: Long
Symmetry: Asymmetrical



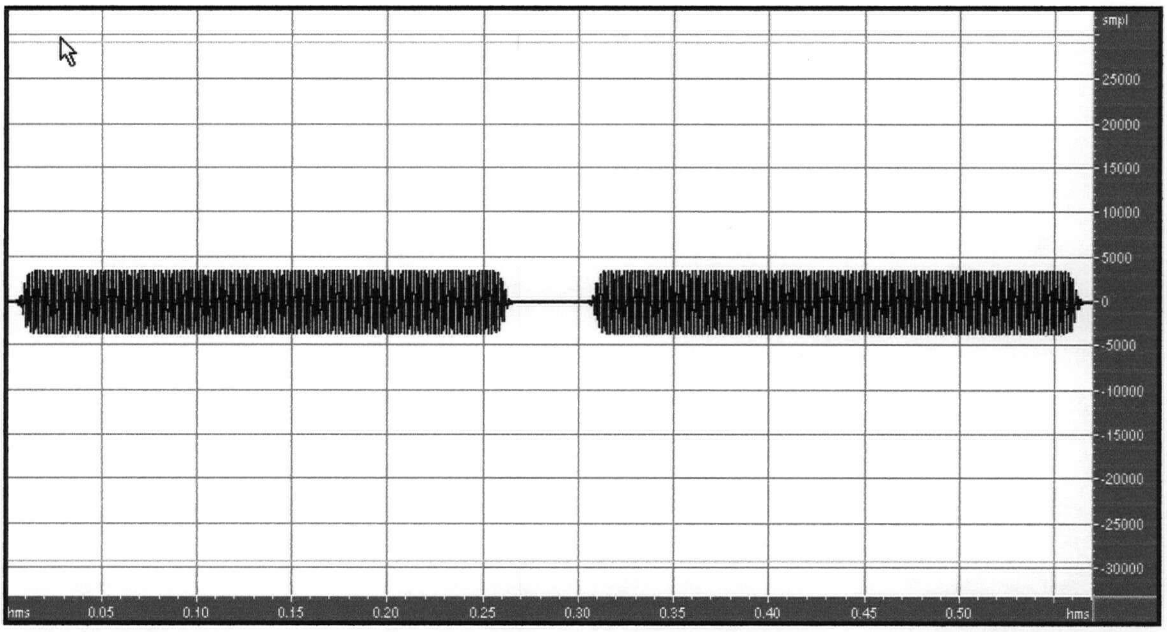


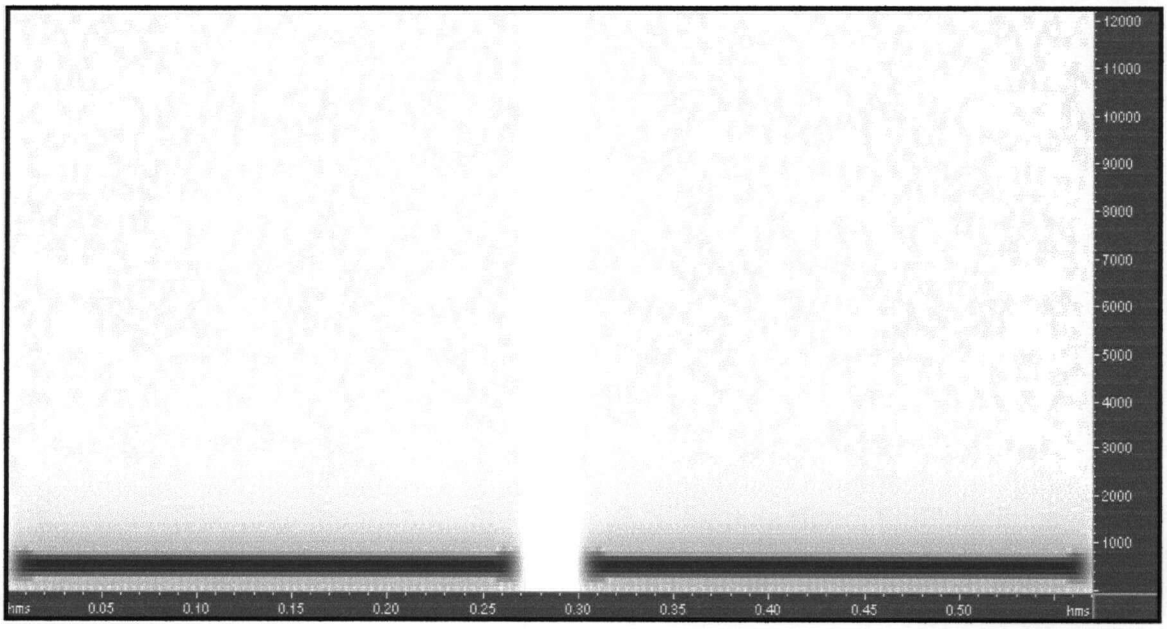
<u>Stimulus Condition 3</u> Type: Non-Speech,
Marker Duration: Short
Symmetry: Symmetrical



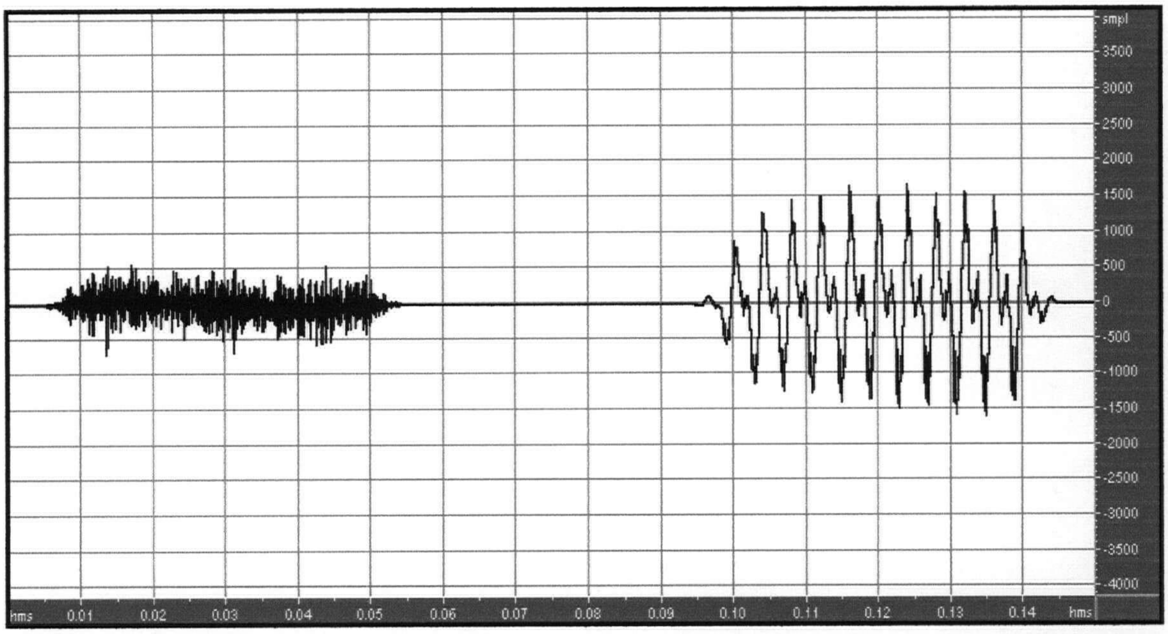


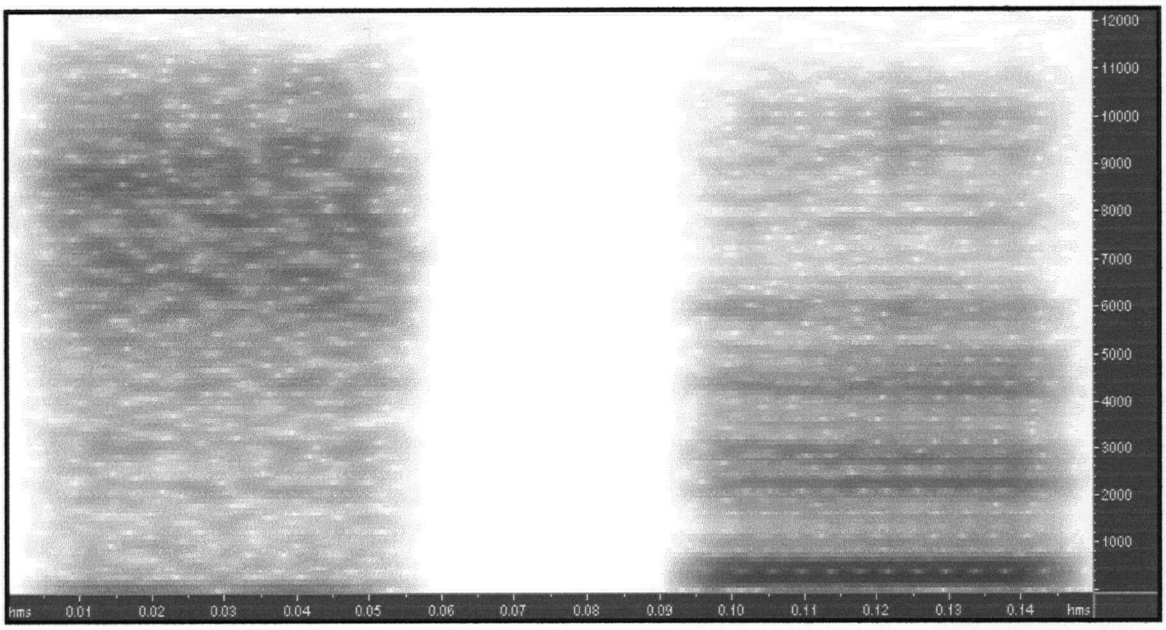
<u>Stimulus Condition 4</u> Type: Non-Speech,
Marker Duration: Long
Symmetry: Symmetrical



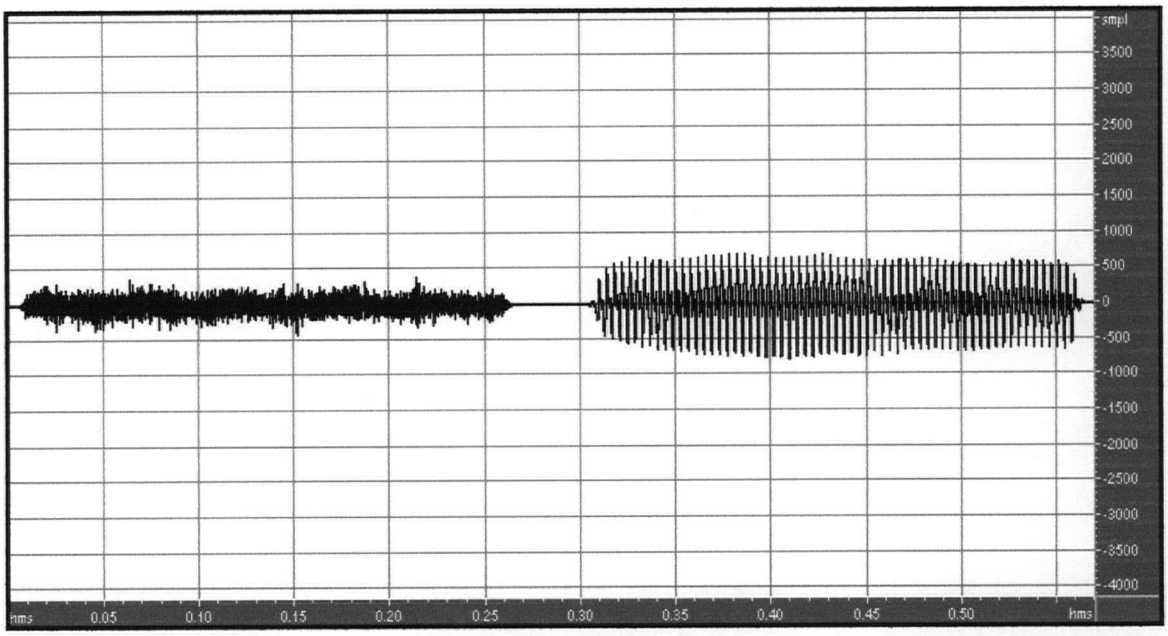


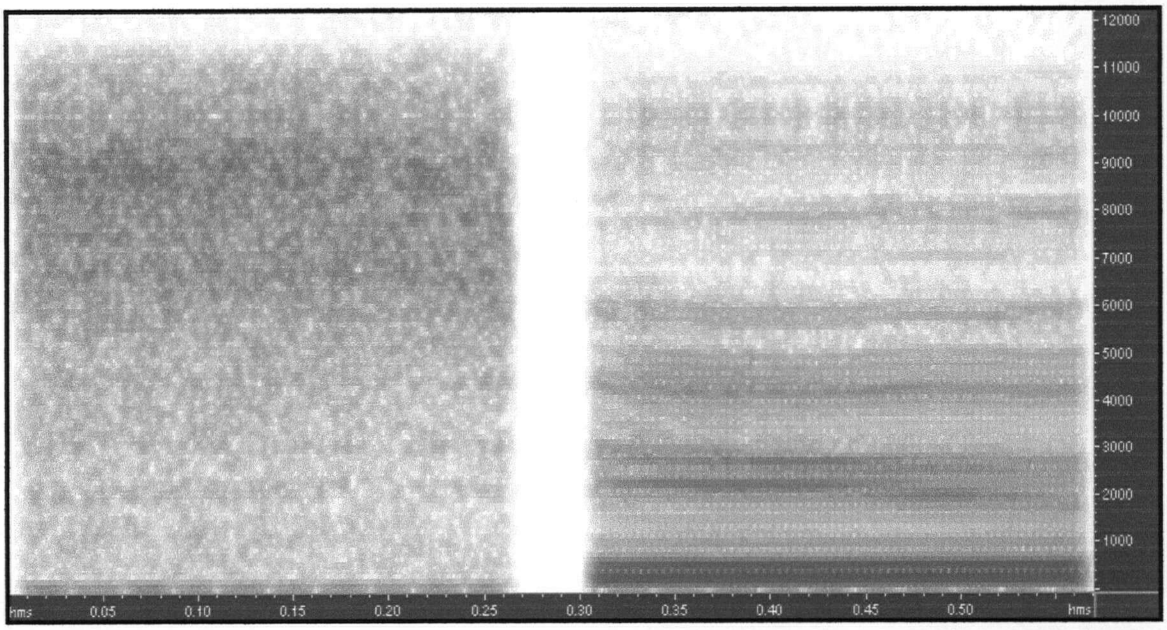
<u>Stimulus Condition 5</u> Type: Speech,
Marker Duration: Short
Symmetry: Asymmetrical



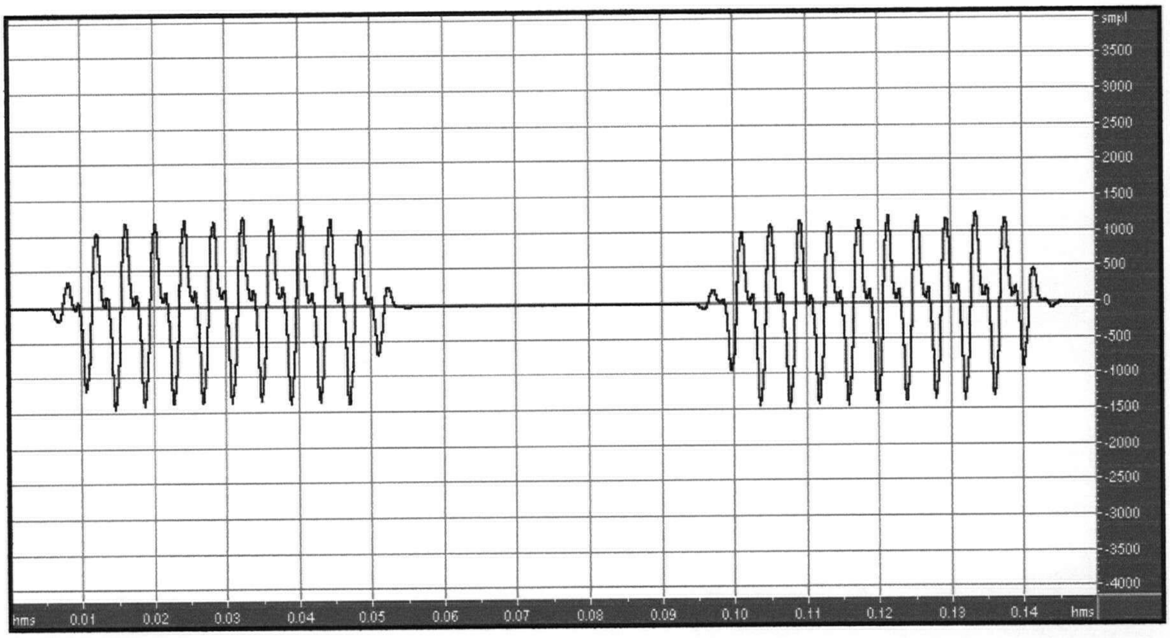


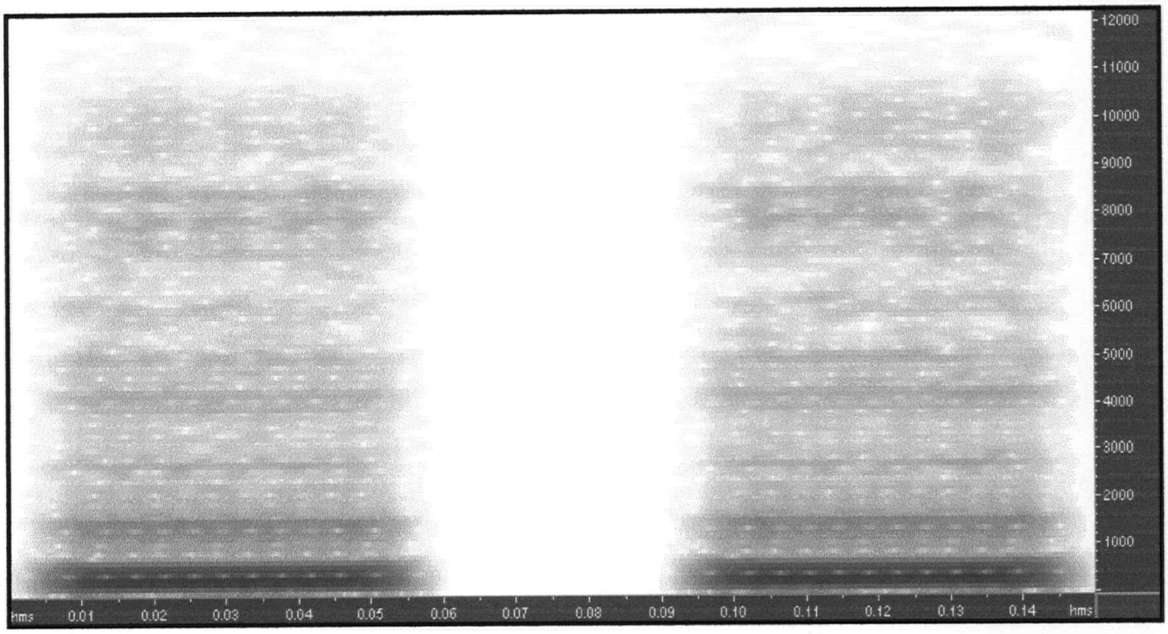
Stimulus Condition 6 Type: Speech,
Marker Duration: Long
Symmetry: Asymmetrical



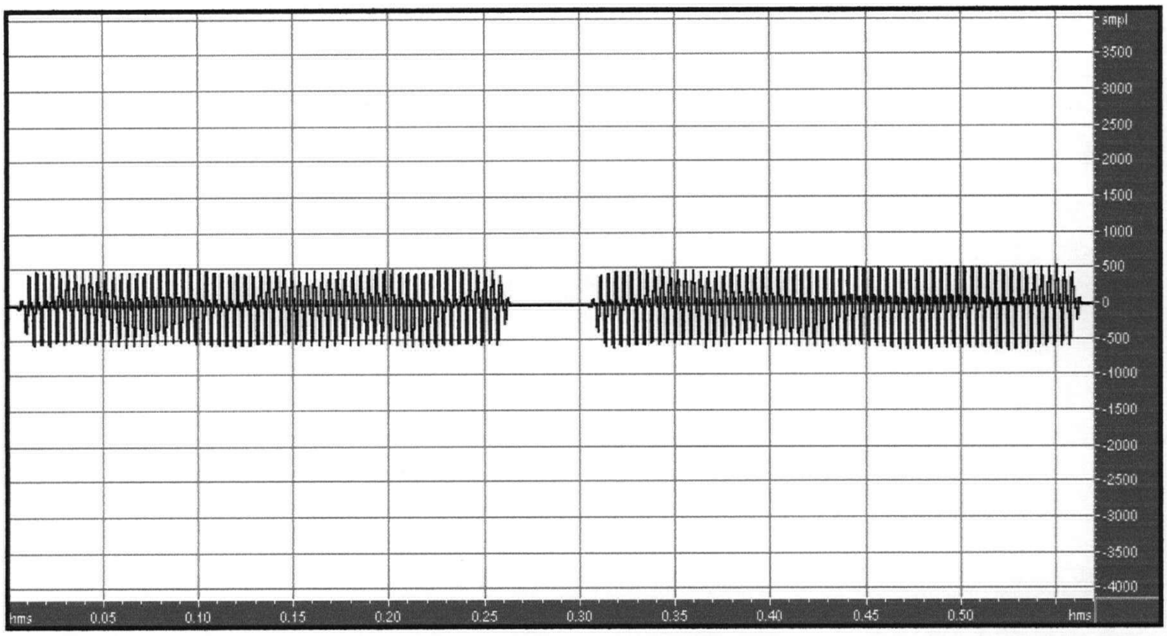


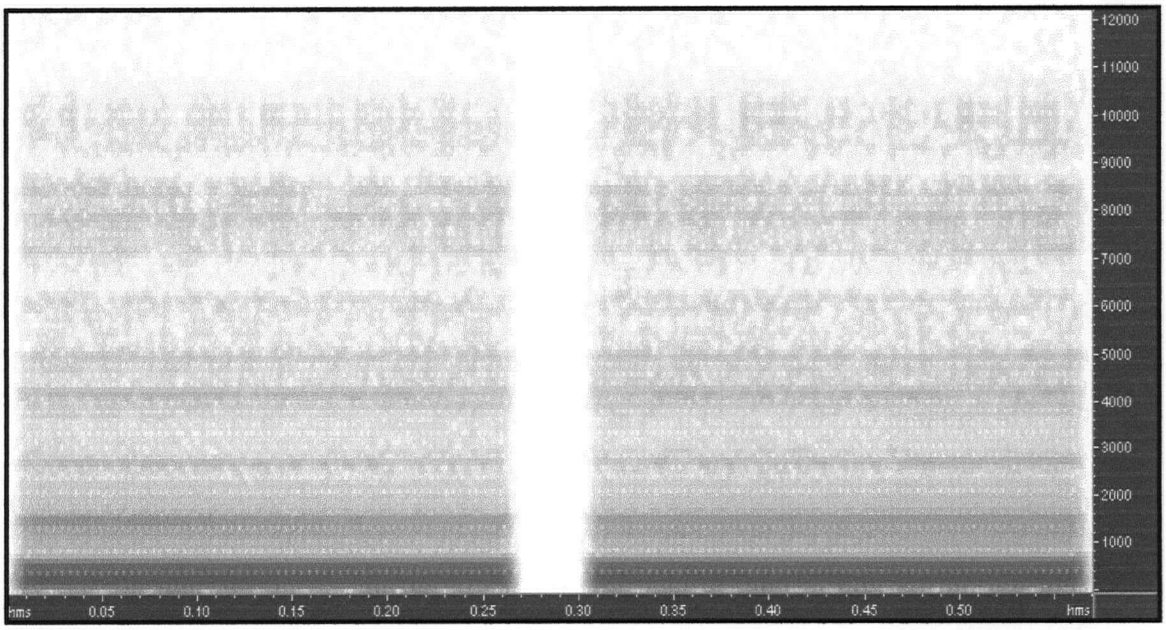
<u>Stimulus Condition 7</u> Type: Speech,
Marker Duration: Short
Symmetry: Symmetrical





Stimulus Condition 8 Type: Speech,
Marker Duration: Long
Symmetry: Symmetrical





APPENDIX E

Instructions to Participants

The purpose of this study is to learn more about how adults of different ages hear sounds that are similar to speech sounds. The results will help us understand how changes in hearing abilities can influence day-to-day communication.

Today, you will sit in this quiet sound booth and listen to different sounds through headphones.

You will hear pairs of sounds. When you hear the first sound, the light on the left will come on. When you hear the second sound, the light on the right will come on.

One of these sounds will have a space, or a gap in it. Your task is to press the button for the sound which you think has the space.

If you think the first sound you heard had the space, you will press the button on the left. If you think the second sound had the space in it, you will press the button on the right.

It is best to wait until you hear both of the two sounds before you press the button for your answer.

After you press the button, a light will come on showing you which of the sounds had the space. Then, you will hear the next pair of sounds. There will be many pairs of sounds.

Are you ready to try a quick practice test?

Do __practise, and wait until 6 consecutive correct

As you listen to more and more pairs of sounds, it will become harder to know which has the space in it. This is because some of the spaces will be smaller.

At first, it will be easy because the spaces are big, but later the spaces will be very small.

Your task is always to press the button which corresponds to the sound which you think has a space in it.

It is important to listen carefully and try to hear even the very smallest spaces.

Sometimes you will not be able to tell which of the two sounds has the space in it. This is a normal part of the test. You should just try your best to guess which sound has the space in it. Even if you are not sure, you have to guess.

Do __vary, and wait until 6 consecutive correct

APPENDIX F

Raw Data: Average Gap Detection Thresholds for Each Subject in Each Stimulus Condition (ms).

These values are the average of the two lowest gap detection thresholds of the three obtained for each subject in each stimulus condition.

Y=younger adult
O=older adult

Partici-pant	Long				Short			
	Speech		Non-speech		Speech		Non-speech	
	S*	A**	S	A	S	A	S	A
Y-1	1.46	22.25	1.32	59.88	4.35	22.25	1.44	68.88
Y-2	1.46	14.50	1.38	52.13	1.64	18.63	1.60	32.63
Y-3	1.39	5.47	1.46	26.75	2.30	5.75	1.24	19.24
Y-4	1.53	11.88	1.34	110.50	3.95	13.00	1.35	74.38
Y-5	1.50	9.63	1.21	24.00	3.15	7.62	1.25	17.13
Y-6	1.58	14.13	1.35	20.50	1.53	6.38	1.17	16.50
Y-7	1.25	8.24	1.33	28.75	1.52	4.86	1.24	14.13
Y-8	2.07	24.25	1.52	72.25	3.55	10.25	1.59	41.88
O-1	4.09	59.25	1.61	251.50	4.74	36.25	2.18	148.38
O-2	1.81	34.75	1.58	55.75	2.03	12.49	1.16	10.33
O-3	4.84	26.75	1.94	104.75	4.99	9.61	1.57	63.00
O-4	4.20	30.38	2.18	308.88	5.61	65.00	2.92	26.50
O-5	1.59	65.38	1.38	95.25	2.20	16.50	1.39	96.63
O-6	2.15	63.63	1.77	128.25	3.54	61.75	2.40	133.75
O-7	3.16	26.88	2.73	38.50	4.47	8.13	1.43	76.25
O-8	1.53	74.88	1.48	46.50	2.07	31.75	3.43	110.00

* S=Symmetrical
** A=Asymmetrical