The Effect of Temporal Envelope Changes on Recognition of Normal Rate and Time-Compressed Speech by Young-Old and Old-Old Hearing-Impaired Listeners

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This is to certify that I have examined this copy of a doctoral dissertation by
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Abstract

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When understanding speech in complex listening situations, older adults with hearing loss face the double challenge of cochlear hearing loss and additional deficits of the aging auditory system. Wide-dynamic-range compression (WDRC) is used in hearing aids as remediation for the loss of audibility associated with hearing loss. WDRC processing has the additional effect of altering the acoustics of the speech signal, particularly the temporal envelope. Older listeners are negatively affected by other types of temporal distortions, but this has not been found for the distortion of WDRC processing. The purpose of this research was to determine how older adult listeners compensate for the temporal envelope changes of WDRC. To answer this question, a two-part approach was used, first incorporating acoustic measures and second isolating the compensatory mechanisms the older listener may be using.

Two groups of adults with mild to moderate hearing loss were tested: young-old (62-74 yrs, n = 11) and old-old (75-88 yrs, n = 14). The groups did not differ on hearing loss, cognition, working memory, or health. Participants listened to low-predictability sentences compressed in quiet at each of four selected compression settings that covered a wide range of acoustic effects, quantified by the Envelope Difference Index (EDI). The sentences were presented at three rates: normal rate, 50% time-compressed, and time-restored.

There was no age difference, nor any interactions between age and listening condition. There was a significant interaction between speech rate and EDI value. As the EDI value increased, representing higher amounts of distortion, speech recognition

was significantly reduced for the third and fourth EDI values relative to the first EDI value. At the fourth EDI value, this reduction was greater for the time-compressed than normal-rate condition.

It can be concluded that temporal envelope changes are detrimental to recognition of low-context speech for older listeners, once a certain threshold of distortion has been reached. The effect is not age-related within the age range tested here. The results of the time-restored condition suggested that listeners were using acoustic redundancy to compensate for the negative effects of WDRC distortion in the normal rate condition.

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Dedication

In memory of Jen.

Introduction

The prevalence of sensorineural hearing loss (SNHL) increases with increasing age. The main consequence of SNHL is loss of audibility for low-intensity sounds. Wide-dynamic-range compression (WDRC), in which the gain provided by the hearing aid depends on the input signal level, is commonly used in hearing aids for its ability to restore audibility of the low-intensity sounds, making these sounds more intelligible for listeners with hearing loss. A side effect of restoring audibility is that WDRC can change important cues in the speech signal, particularly the temporal envelope of speech, which is the slow time-intensity modulation of speech. This envelope carries information about syllable structure and rhythm, providing cues for identification of voicing and manner (Jenstad & Souza, 2005; Van Tasell, 1993). The amount of change to the temporal envelope depends on the specific WDRC parameters chosen. In many instances, old-old adults (age 75 and above) have been shown to be more susceptible than young (below age 60) or young-old (60-74 yrs) adults to the effects of conditions that distort or degrade the speech signal[1]. Research to date has not shown this to be the case for the distortion caused by amplitude-compressing simple speech signals (Souza & Kitch, 2001).

The purpose of this research is to determine how old-old adults with hearing loss compensate for the temporal envelope changes associated with WDRC processing. To answer this question, a two-part approach is required. The first part involves careful consideration of the acoustic properties of WDRC processing. Previous research shows that even though parameter settings may change nominally, the actual acoustic change may be much less than thought (e.g., Stone & Moore, 1992). Thus, it is important to measure the acoustic change of any conditions that are to be compared behaviorally to ensure that they are, in fact, different. The second part of this approach is to determine, and isolate, any mechanisms that the listener may be using to compensate for acoustic distortions caused by WDRC processing.

Cochlear Hearing Loss

Because this research question involves listeners with hearing loss, it will be important to first understand the characteristics of the auditory system and the deficits associated with cochlear hearing loss. One of the hallmarks of the normal auditory system is its ability to encode a very wide dynamic range of intensities. This is accomplished by an active mechanism in the cochlea, also known as the "cochlear amplifier," which is mediated through healthy outer hair cells (OHCs) (Moore, 1996; Moore, Vickers, Plack, & Oxenham, 1999; Robles & Ruggero, 2001). In a healthy cochlea, the physiological response of the basilar membrane (BM) to a wide range of input levels is one of compressive nonlinearity. The compression is greatest for mid to high intensities; that is, a large increase in input level results in only a small change in the

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[1] The term "older" adult will be used to include all adults aged 60 years and older. Finer age distinctions will be indicated by the terms "young-old" (age 60-74) and old-old (age 75 and above).

physiological response. For low intensities, the BM response is effectively linear (Robles & Ruggero, 2001).

The nonlinear BM transfer function can be understood by examining the mechanics of the BM together with the function of OHCs. OHCs have an active role in changing the response to a signal through their motility. Contractions and elongations of the OHC cell body change the sensitivity of the auditory system, which effectively provides amplification for low-level sounds and compressive nonlinearity for mid-level (and possibly high-level) sounds (Dallos, 1997; Hudspeth, 1997; Spector, Brownell, & Popel, 1999).

The behavioral consequence of the nonlinear physiological response is a nonlinear growth of loudness in normal hearing ears (Moore & Glasberg, 2004). In listeners with normal hearing, as the intensity of the signal increases from threshold up through the dynamic range of the listener, perceived loudness also increases, but at a slower rate. Other behavioral correlates of BM nonlinearity include sharp frequency tuning and a wide dynamic range of hearing.

With most types of cochlear hearing loss, many or all of the OHCs are destroyed, resulting in the loss of basilar membrane nonlinearity (Moore, 1996). Loss of BM nonlinearity means a loss of audibility for low-level sounds, due to the absence of the amplifier. It also means a loss of nonlinear growth of loudness. For listeners with hearing loss, it means they have the inability to hear low-level sounds, reflected in raised auditory thresholds, but they perceive high-level sounds at normal or near-normal loudness. The dynamic range of hearing is reduced with cochlear hearing loss relative to the dynamic range of hearing for normal hearing (Moore & Glasberg, 2004).

This presents a problem for hearing aid fitting: in order to make low-level sounds audible, the hearing aid must provide sufficient gain to increase the sounds above the listener's threshold. However, equal gain cannot be applied to all input levels without causing loudness discomfort. Wide-dynamic-range compression (WDRC) hearing aids are commonly used to overcome this challenge, but this processing may introduce other changes that are not helpful to the hearing-impaired listener.

In addition to altered loudness perception, people with cochlear hearing loss lose the sharp frequency tuning also attributable to the active mechanism (Moore & Glasberg, 2004). This may result in a reduced ability to use the frequency information in signals. In a series of studies of amplitude versus spectral cue weighting, Hedrick and colleagues confirmed that listeners with normal hearing and hearing loss had different strategies in the weight applied to each cue (Hedrick, 1997; Hedrick & Carney, 1997; Hedrick & Jesteadt, 1996; Hedrick, Schulte, & Jesteadt, 1995; Hedrick & Younger, 2001). The researchers in these studies used stimuli that varied in relative amplitude of the consonant and spectral information of the formant transitions and used a categorical perception paradigm to determine how much weight listeners placed on each of the cues. Listeners with normal hearing applied about equal weight to the temporal and spectral cues. Listeners with hearing loss placed greater weight on the amplitude cues for perception of place of articulation for both stops and fricatives (Hedrick, 1997; Hedrick & Jesteadt, 1996; Hedrick et al., 1995). It is possible that the greater reliance on amplitude than spectral cues might have been due to inaudibility of the high-frequency spectral information. To separate the effects of audibility and listening strategy, a follow-up study was conducted that controlled for audibility differences of the spectral information. The greater reliance on temporal information than spectral information was still apparent for listeners with hearing loss when the spectral information was audible (Plyler & Hedrick, 2002). Hearing impaired listeners using cochlear implants also show this alternate pattern of cue weighting, placing up to 13 times more weight on the amplitude cue than the spectral cue for perception of place of articulation (Hedrick & Carney, 1997).

Cochlear Hearing Loss and Older Adults

The prevalence of hearing loss increases with age, with 41% of adults aged 60 years and older reporting hearing difficulties (Gates, Cooper, Kannel, & Miller, 1990). For a given individual, hearing thresholds decline an average of .7 to 1.23 dB at each audiometric frequency per year after the age of 60 years (Lee, Matthews, Dubno, & Mills, 2005). Age-related hearing loss (presbycusis) is a catch-all term that includes many types of hearing loss found in older individuals, such as noise exposure, genetic factors, and systemic causes associated with aging that are difficult to truly separate (Kiessling et al., 2003; Lee et al., 2005). Despite the many possible causes of hearing loss in older people, the majority of the losses are sensorineural. This means that the general effects of hearing loss in age include the same deficits described above; namely, loss of audibility for low-level sounds and loss of basilar membrane nonlinearity (Frisina, 2001; Kiessling et al., 2003; Willott, 1996).

Behavioral Evidence for Temporal Changes with Age

In addition to the loss of audibility and loss of nonlinearity that older adults with cochlear hearing loss experience, older listeners also have additional damage at multiple possible sites that may lead to widespread processing deficits, such as destruction of the stria vascularis or loss of neural synchrony (Kiessling et al., 2003; Willott, 1996). Older listeners have reduced temporal processing for some types of temporal cues. I will focus this discussion on older adults' use of the temporal envelope (the slower modulations), rather than the faster modulations. Evidence shows that the ability to use suprasegmental envelope cues, such as prosodic information, is preserved with age (Wingfield, Lindfield, & Goodglass, 2000). However, detection of the local features of the temporal envelope, such as gaps and duration, is reduced with age (Schneider, Speranza, & Pichora-Fuller, 1998). In relation to speech perception, this means that older listeners can extract information about the number of syllables and syllabic stress from the temporal envelope to the same degree as younger listeners. However, when gaps and duration carry important information about the identify of specific phonemes, older adults have been shown to need longer gaps and longer durations to extract the relevant information (Price & Simon, 1984).

With many studies of aging listeners, hearing loss is often a confound in interpreting the results. The question is whether the above results can be attributed to higher-level processes associated with aging, or with cochlear hearing loss that often accompanies aging. For instance, Boike (2004), in her unpublished dissertation, found that her older subjects had poorer modulation detection thresholds than younger listeners, but statistically, much of this variance could be explained by slight differences in hearing thresholds. However, Fullgrabe and colleagues (Fullgrabe, Meyer, & Lorenzi, 2003), while not specifically examining older listeners, approached the question of whether temporal processing (as measured by modulation detection and modulation masking, similar to the Boike dissertation) was affected only by cochlear damage and found that temporal processing was unchanged in listeners with cochlear damage. From the results of such findings, it is probable that changes in temporal processing observed for older hearing-impaired listeners are due to age-related changes to mechanisms beyond cochlear hearing loss.

Physiological Evidence for Temporal Changes with age

Physiological studies of young and old rats and mice have been conducted specifically to confirm the behavioral evidence of an age-related decline in temporal processing and to determine the underlying mechanism responsible for the age-related changes. The combined evidence from several studies of neurons in the inferior colliculus points to several age-related declines. With respect to gap detection, two changes are apparent: in older mice, fewer neurons are capable of responding to very short gaps in a signal; also, the older neurons exhibit slower recovery after the gap (Walton, Frisina, & O'Neill, 1998). With respect to modulation transfer functions, there is a change in the number of neurons responsive to specific amplitude modulation rates in older animals. The main disruption occurs for higher modulation rates (Shaddock Palombi, Backoff, & Caspary, 2001; Walton, Simon, & Frisina, 2002). This is thought to reflect changes in neural synchrony.

Aging and Speech Recognition

Speech recognition has been well-studied in older adults, with evidence that speech recognition declines with increasing age (Cheesman, Hepburn, Armitage, & Marshall, 1995; Divenyi & Haupt, 1997, 1997, 1997; Gelfand, Piper, & Silman, 1986; Souza, 2000; Souza & Kitch, 2001). Defining older listeners has been the subject of some debate. The exact age group used to test older listeners is widely variable across studies, sometimes including all listeners over a specific age as a single “older” group, or limiting subjects to an upper age limit (of 75 years and below, for example). Greater reductions in speech recognition than would be predicted by threshold change are more likely seen in “old-old” listeners (over 75 years) than in “young-old” listeners (age 65 to 75 years) (Magnusson, 1996; Sherbecoe & Studebaker, 2003). A mean age difference of 10 years can have a large effect on the results of different studies (as noted in Souza, 2000). This difference is independent of the amount of hearing loss, shown by Humes and Christopherson (1991) where their old-old subjects performed worse for filtered and reverberant speech than the young-old, despite equivalent hearing losses.

The research challenge put forth by CHABA in 1988 was to determine the source of this deficit (CHABA, 1988). Speech recognition could be reduced due to peripheral changes, central auditory changes, or general cognitive changes. Figure 1 shows a simplified model of these three hypotheses.

(Figure 1)

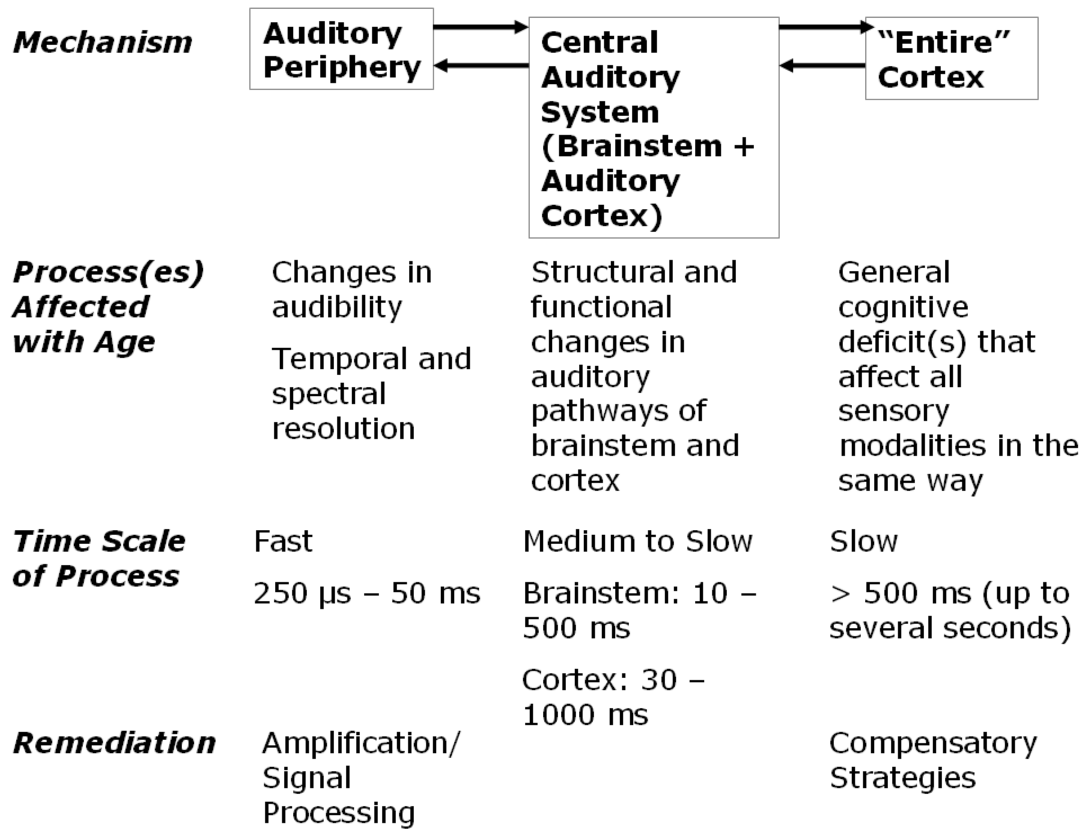

Figure 1. Simplified model of the mechanisms of speech recognition that may be affected with age, the time course of the processes involved, and the implications for remediation.

According to the peripheral hypothesis, any reduction in speech recognition with age is due to the greater prevalence of peripheral hearing loss for elderly listeners. For simple speech; that is, speech in quiet that has not been degraded, reductions in recognition for most older listeners can be explained by worse hearing thresholds in older listeners, consistent with the peripheral hypothesis. This finding has been demonstrated for vowel perception in quiet (Nabelek, 1988), nonsense syllable perception (Helfer & Huntley, 1991), and word recognition in quiet (Dubno, Lee, Matthews, & Mills, 1997). Importantly, this relationship holds true for most speech that has not been temporally distorted (Humes, 1996).

Not all speech understanding in older listeners is explainable by the simple audibility model. Some older individuals have difficulties in quiet speech understanding to an extent not explainable by their hearing loss and an even greater proportion of older listeners have difficulty with complex listening situations. For these listeners, the difficulties could be associated with one or more of the three hypotheses: additional peripheral damage that is not reflected on tests of pure-tone thresholds, damage specific to the auditory brainstem and cortex, or general cognitive changes, not specific to the auditory system.

Age, independent of peripheral hearing loss, becomes a more important contributor to speech recognition for complex listening tasks (Schum, Matthews, & Lee, 1991), indicating that one of the other mechanisms must be important for complex listening. Older adults, particularly old-old listeners, tend to have more difficulty than younger listeners in noise, and even more difficulty when the background noise is temporally modulated (Dubno, Horwitz, & Ahlstrom, 2002). Speech recognition performance is also reduced for older adults listening to speech that has been distorted by reverberation or other temporal manipulation (Helfer & Huntley, 1991; Humes, 1996; Nabelek, 1988), or speech made less redundant by removing a cue dimension or placing acoustic cues in competition (Coughlin, Kewley-Port, & Humes, 1998; Dorman, Marton, Hannley, & Lindholm, 1985; Ohde & Abou-Khalil, 2001). While it is difficult to separate out the effects of aging from the effects of greater hearing loss found in older adults, studies that have employed careful controls for hearing loss have shown that increasing age is a predictor of reduced speech recognition under these distorted or degraded listening conditions (e.g., Studebaker, Sherbecoe, McDaniel, & Gray, 1997).

Attributing speech recognition declines to “aging” is simply a way of saying that the deficit goes beyond cochlear hearing loss. The model in Figure 1 gives one framework in which to examine the deficits associated with aging. Changes could be occurring at the peripheral, central auditory, or cognitive levels. The peripheral hypothesis includes, but is not limited to, threshold change. As with simple speech recognition, the main consequence of threshold change is to make portions of the speech signal inaudible, rendering recognition difficult. One mistake often made in the literature is to assume that threshold measurements will reflect all peripheral changes. Thus, if thresholds do not statistically explain all of the variance in speech recognition, often the conclusion is that the changes must be either central auditory or general cognition. In one example of this logic, hearing loss was simulated in young listeners using noise-reduction earplugs, who were then tested on speech recognition and cognitive tasks. When the young listeners’ performance was not degraded as much as older listeners’ performance on the same tasks, the authors concluded that peripheral changes had no effect on cognitive tasks relying on auditory input (Lindenberger, Scherer, & Baltes, 2001). However, peripheral damage could also include changes that are not reflected in audiometric measurements of threshold, particularly when threshold is simulated with a conductive hearing loss.

At the higher-level extreme, the cognitive hypothesis of reduced speech understanding includes three major theories to explain the cognitive changes seen with age (Hasher, Tonev, Lustig, & Zacks, 2001): reduced processing speed, reduced resource capacity, or reduced inhibition for irrelevant items. The cognitive hypothesis is relevant only if it can be shown that deficits are quantitatively and qualitatively similar across sensory domains and tasks (Bashore, vanderMolen, Ridderinkhof, & Wylie, 1997). If the deficits differ across domains and tasks, then the change is likely not due to general cognitive change, but to deficits occurring within the perceptual domain relevant for the tasks.

In the middle of these two possibilities is the central auditory hypothesis. This hypothesis comes into play when the deficits observed in speech recognition cannot be attributed either to peripheral damage (including peripheral damage *not* reflected on threshold measurement) or to general cognitive declines. The central auditory hypothesis posits that damage is anywhere in the brainstem or auditory cortex that is specific to the auditory pathway.

Much of the research data has shown that perception and cognition co-vary with age, making it very difficult to distinguish among the peripheral, central auditory, and cognitive deficits that may be occurring with aging (Schneider, 2001). Several explanations are used for this covariance: perceptual decline may cause cognitive decline (either through long-term sensory deprivation or short-term information degradation); cognitive decline may cause perceptual decline (cognitive load on perception theory); or there may be an independent third cause for both declines (common-cause theory) (Schneider & Pichora-Fuller, 2000).

The interaction between peripheral and central processing may also have some positive aspects for speech recognition. Schneider and Pichora-Fuller (2000) note that declines in bottom-up processing are offset by attention to the broader context, implying that there are ways to compensate for peripheral damage or a degraded input signal. If the sensory input is degraded, the listener may still be able to interpret the message by using higher-level resources. The compensation by other resources adds to the difficulty of isolating the contribution of peripheral damage to speech recognition. For example, speech in one listening condition may be recognized mainly via bottom-up mechanisms, while speech in a degraded listening condition may force the listener to use general knowledge and context (higher-level mechanisms) to recognize the signal. The behavioral scores in terms of percent correct may be the same for both of these conditions, but from the person’s response, there is no way of separating how much of the recognition was due to peripheral contributions and how much was due to central or cognitive contributions.

Let us look at the acoustic and linguistic characteristics of some of the commonly-studied listening tasks and their effects on speech recognition. How do the results for each type of listening, particularly for degraded or distorted conditions, tie in with the three hypotheses for reduced speech recognition in young-old and old-old listeners? Where possible, the results are reported separately for young-old and old-old listeners. If these two age groups were not distinguished in the original research article, the participants will be described under the general term “older listeners.”

Background noise

Background noise is difficult to summarize because it can constitute any unwanted sound in a listening situation. The properties that may vary include spectral content, modulation depth and frequency, duration, meaningfulness, overall level, and level relative to the signal of interest. A common property of many noise types, however, is masking of low-level speech segments (Nabelek, 1993).

For steady state noise, speech recognition is reduced predictably by the reduction in audibility of the speech signal (Dubno et al., 2002; Dubno et al., 1997; Tun & Wingfield, 1999). It functions in the same way as peripheral hearing loss does to reduce audibility. This relationship does not hold true at high levels of steady background noise, as the reduction in recognition is greater than expected from the audibility loss (Humes et al., 1994). This change in the pattern at high levels indicates that another mechanism, other than audibility, is affected by high noise levels. This could, however, still be a peripheral effect.

For more complex background noise, such as temporally-modulated noise, multi-talker babble, or tone complexes, speech recognition among older listeners does not have a simple, predictable relationship to changes in audibility. In most studies of young-old listeners, the effect of modulated noise has been found to be mostly peripheral and related directly to audibility changes (Gordon-Salant, 1987, 1987; Gordon-Salant & Fitzgibbons, 1995, 1995, 1997; Schneider, Daneman, Murphy, & See, 2000). There are some exceptions, though, in which even in this young-old group it has been found that the difference between the speech recognition score predicted from audibility and the actual score for the young-old listeners is greater in a temporally-modulated background noise than in steady-state noise (Dubno et al., 2002; Sherbecoe & Studebaker, 2003). However, Dubno et al. (2002) found that the greater deficit for temporally-modulated background noise was related to the listener's masked thresholds, also a peripheral effect.

For old-old listeners, while peripheral changes in audibility are still important predictors of speech recognition in modulated noise, other factors have a larger role. For example, verbal and non-verbal cognitive factors (Humes, 2002), working memory (Pichora-Fuller, Schneider, & Daneman, 1995), and changes in temporal processing have been associated with reduced speech recognition in modulated noise. Additionally, a non-specific "age" factor has also been found to be associated with reduced recognition in complex noise. The nature of this factor is such that, once hearing loss has either been controlled or accounted for statistically, a significant portion of the variance in scores can be accounted for by the listener's age (Frisina & Frisina, 1997; Helfer & Huntley, 1991; Nabelek, 1988).

Meaningful background noise is distinguished from other modulated noise because it likely engages higher-level processes. Noises included in this category are backgrounds of one or two talkers speaking in a language familiar to the listener. Both younger and older listeners benefit when the number of background talkers is reduced from multiple talkers to a single talker, but older adults do not get as much benefit as younger adults (Tun & Wingfield, 1999). The age effect is minimal when the single background talker speaks an unfamiliar language (Tun, O'Kane, & Wingfield, 2002), indicating that the reduced benefit for older listeners is not simply peripheral masking. This finding is likely related to cognitive factors, which may be either reduced inhibition or reduced processing resources (Tun et al., 2002). The age effect for meaningful background noise is greater for old-old than young-old listeners (Beaman, 2005).

Reverberation

Reverberation has two main effects on the acoustic speech signal: first, it causes masking of the signal, thereby reducing audibility, and second, it changes the temporal structure of the speech signal (Helfer & Huntley, 1991). Masking of the signal, also known as overlap-masking, occurs when the reflected acoustic signal of one speech segment reduces the audibility of the next speech segment. The amount of masking depends on the relative intensities of the two speech segments and the amount of shared spectral content. Changes to the temporal structure of the signal come from self-masking, when the reflected acoustic signal smears the energy within a phoneme, essentially filling in the low-intensity portions of the signal, thereby reducing the modulation depth (Humes, 1993; Nabelek, 1993). The change to the temporal structure is greater for higher modulation frequencies than lower ones.

Reverberation has been found to have a detrimental effect on recognition even for young-old listeners (Gordon-Salant & Fitzgibbons, 1993, 1995, 1995), and is greater for old-old listeners (Humes & Christopherson, 1991; Nabelek, 1988). The effect is particularly evident when reverberation is combined with a second distortion and is not due simply to peripheral hearing loss. Individual susceptibility to the negative effects of reverberation is correlated with measures of temporal processing (Gordon-Salant & Fitzgibbons, 1993; Humes & Christopherson, 1991).

Acoustic cue manipulation

Another type of listening task used to study speech recognition in older adults is one in which listeners are presented with minimal acoustic information, and the relevant acoustic cues are modified, distorted, or even removed. In these acoustic cue manipulation studies, listeners are forced to use minimal acoustic cues to recognize the speech signal. The stimuli may be created in several possible ways: synthesizing stimuli that vary on only one parameter; putting two acoustic cues in competition to determine the weight that the listeners applies to each one; removing portions of the signal, such as the steady-state portion of a vowel while leaving only the dynamic cues (i.e., formant transitions); or providing the listener with a very impoverished acoustic signal. These paradigms have in common that they remove redundancy from the signal to determine which acoustic cues the listeners are weighting the highest for recognition.

Conflicting results have been found from various studies using this approach. However, the general conclusions that can be drawn are that older adults are less able than younger adults to use the dynamic cues of speech as sources of information (Fox, Wall, & Gokcen, 1992), they are less efficient listeners (Ohde & Abou-Khalil, 2001), they are less able to use the second formant to identify vowels (Coughlin et al., 1998), and they need to integrate acoustic cues more than younger listeners (Ohde & Abou-Khalil, 2001). This last finding means that older listeners need more redundancy in the signal, and in particular, do not perform well when the acoustic cues are in conflict.

The source of these effects is not well known. In one rather compelling study, it was shown that both normal-hearing and hearing-impaired older listeners' reduced ability to discriminate /ba/ and /pa/ on the basis of voice onset was related to their abnormal cortical responses (Tremblay, Piskosz, & Souza, 2003). The abnormal response was found for the N1-P2 response, but not an earlier-occurring cortical response (P1). This differentiation provides some evidence that this particular age-related difficulty occurs in the central auditory nervous system, but not in the peripheral system.

Other temporal manipulations

The finding in many of these studies that reduced speech recognition with increased age was associated with temporal resolution has led to the study of several temporal manipulations of the speech signal. A partial list of these manipulations includes interrupted speech, jittered speech, altered duration of specific segments, and altered amplitude relationships, such as the consonant-vowel ratio (CVR). Reduced recognition by older listeners has been found specifically for interrupted speech (Gordon-Salant & Fitzgibbons, 1993). Reduced recognition by listeners of *all* ages, not just older listeners, have been found for manipulations in which duration or relative amplitude were altered (Gordon-Salant, 1986).

One of the most well-studied forms of temporal distortion in older listeners is rapid speech, also known as time-compressed speech. Time-compressed speech is used extensively to investigate the separate contributions of perceptual and cognitive processes to speech recognition in older listeners. In everyday conversation people tend to talk more quickly than the rate used for standard speech testing, so rapid speech is one way of making the lab tests more realistic. For purposes of better experimental control over the variables that may change when a talker adjusts his or her rate, time-compressed speech is often used to simulate faster talking rates. Time compression of speech is implemented by removing regular intervals from the speech signal and abutting the remaining segments using some weighted overlap of the segments to eliminate clicks and distortions in the signal. This method does not change the pitch of speech and sounds quite natural and intelligible (Arons, 1992). As more time compression is applied, representing faster speaking rates, older listeners show greater reductions in speech recognition. This effect is more pronounced when time-compression is combined with processing that distorts the acoustic signal, such as reverberation or complex background noise (Gordon-Salant & Fitzgibbons, 1995, 2004; Tun, 1998). Due to this consistent finding, much work has been done with rapid speech to determine the source of the effect.

A large body of evidence points to the reduction in available processing time during rapid speech as the main cause for reduced recognition (e.g., Gordon-Salant & Fitzgibbons, 2004; Tun, 1998; Wingfield, Poon, Lombardi, & Lowe, 1985; e.g., Wingfield, Tun, Koh, & Rosen, 1999). However, there is also some aspect of rapid speech that reveals peripheral deficits for older listeners, independent of degree of cochlear hearing loss (Wingfield, 1995). For example, when speech is time-compressed and then restored to its original length with pauses, older listeners' performance improves but does not return to its original level (Wingfield & Ducharme, 1999). Gordon-Salant and Fitzgibbons (2001) further examined this effect by applying time compression to either an entire sentence or specific parts of the signal. The parts of the signal time-compressed were either consonants only, vowels only, or pauses only. If processing time was the only determinant of the age effect for rapid speech, then the reduction in recognition should be the same for time compression of consonants, vowels, and pauses, provided that the amount of time removed was the same. What Gordon-Salant and Fitzgibbons found was that, although there was an age effect for selective time compression of vowels and pauses, there was a greater age effect for selective time compression of consonants, showing that reduced processing time was an important element of the age effect, but also that the older listeners had greater difficulty processing the rapid acoustic cues or making use of the impoverished acoustic signal.

Recognition of time-compressed speech has been shown to be particularly dependent upon the amount of linguistic context available to older listeners. For normal sentences with full linguistic cues, recognition of the speech is robust despite large amounts of time compression. However, when linguistic cues are removed by presenting the same sentences but the words in random order, recognition by older listeners declines more rapidly than for younger listeners (Gordon-Salant & Fitzgibbons, 2001; Wingfield et al., 1985). This appears to be evidence that there is some processing decline for rapid speech but older listeners can compensate for this decline by using linguistic knowledge.

Multiple Distortions

When two or more of these acoustic degradations are combined in a listening situation, particularly when one of the degradations is time compression, the effect for older listeners is almost always greater than would be expected from the results of each acoustic degradation alone (e.g., Gordon-Salant & Fitzgibbons, 1995; e.g., Gordon-Salant & Fitzgibbons, 1995). Such a finding indicates that with only a single distortion, the older listener may be taking advantage of the redundancy in the speech signal to compensate for the cues that have been altered by the distortion. The addition of a second distortion removes the possibility of accessing the redundant cues.

In summary, recognition of distorted or degraded speech by older adults involves many factors. Several types of temporal distortions have been shown to have negative consequences on speech recognition, particularly if the listening condition involves multiple distortions, or an impoverished speech signal. There is strong evidence that this effect is not caused only by peripheral hearing loss. The effect increases with age, even within the category of “older” listeners.

The three hypotheses for complex speech recognition decline in aging have important consequences for remediation of hearing loss. Recognition decline associated with peripheral damage can best be remediated by amplification sound processing. Declines associated with either central auditory or cognitive mechanisms will not necessarily be helped by amplification processing (although inappropriate processing could make the listening situation more difficult by introducing additional signal distortion). At the cognitive level, declines are best remedied with compensation strategies, such as use of context, asking the talker to speak more slowly and with pauses, and relying on visual cues provided by the talker. At the central auditory level, remediation may involve listening training (Tremblay, Kraus, McGee, Ponton, & Otis, 2001) or amplification systems that improve the signal to noise ratio, such as personal FM systems.

Amplification Strategies

To compensate for the loss of audibility caused by hearing loss, the primary remediation technique is hearing aids, particularly compression hearing aids that apply differential amounts of gain for different input levels. The main benefit of WDRC derives from its ability to increase audibility of low-intensity sounds (e.g., Jenstad, Pumford, Seewald, & Cornelisse, 2000; Jenstad, Seewald, Cornelisse, & Shantz, 1999; Plomp, 1994; Souza & Bishop, 1999, 2000; Souza & Turner, 1998, 1999).

This strategy has been available for hearing aid amplification for many years and is now standard in most hearing aids fitted (Dillon, 1996; Strom, 2003). The strategy remains the same over time, but the specific implementation changes as we gain knowledge of auditory physiology or hearing aid technology improves. How is increased audibility achieved and what are the spectral and temporal consequences? Generally, audibility is increased either by reducing the range of speech levels within an utterance or reducing the range of speech levels across utterances while maintaining the relative speech levels within an utterance. The reduction in range depends upon both the specific compression parameters (Souza & Turner, 1996, 1998, 1999) and the frequency of the input test signal (Verschuure et al., 1996). As the range of levels is reduced within an utterance, audibility can be increased only at the expense of other, potentially important cues in the speech signal. The benefits of increased audibility may be offset by the potentially harmful effects of distortion on the signal.

The increased audibility generally leads to improved speech recognition for speech presented in quiet, particularly for low input levels (e.g., Humes et al., 1999; e.g., Jenstad et al., 1999; Souza & Turner, 1996, 1998). However, counterevidence demonstrates that increased audibility is not the only important factor for recognition.

For example, De Gennaro, Braida, and Durlach (1986) tested the trade-off between increased audibility and speech distortion for listeners with severe hearing loss, using a compression system that increased audibility by increasing the compression ratio of the system in 16 frequency bands. As compression ratio increased, making compression more extreme, speech recognition decreased, despite the increase in audibility.

The trade-off between audibility and distortion depends upon the type of compression used. Wide-dynamic-range compression (WDRC) operates on the entire range of speech. It is characterized by a low compression threshold, such that all inputs above the threshold are compressed. WDRC can be divided into at least two types, differentiated by the time constants of the compressors: slow-acting WDRC and syllabic WDRC.

Slow-acting WDRC

Slow-acting WDRC, also known as automatic volume control, has a relatively quick attack time and a long release time, longer than the length of a syllable. The purpose of this type of WDRC is to maintain the overall output level of the hearing aid, regardless of the average input level to the hearing aid (Van Tasell, 1993). This means that the level of low-intensity speech would be increased overall, increasing audibility. However, the level relationships within speech, that is, the differences between high-intensity vowels and low-intensity consonants would not be altered. Thus, the audibility of low-intensity consonants would not be increased beyond that of merely increasing the overall level of the speech.

Syllabic WDRC

Syllabic compression has a much faster release time, such that the audibility of low-level consonants can be increased without increasing the level of high-intensity vowels. Syllabic compression leads to a greater reduction in the range of speech levels than does slow-acting WDRC. This has the consequence of altering the level differences between vowels and consonants, a cue that may be useful in identifying particular consonants.

From a physiological perspective, if compression is meant to replace the nonlinear functioning of outer hair cells, fast-acting compression is more desirable because the hair cell action is very rapid. In addition, theoretically the nonlinearity should occur in a large number of processing channels to mimic the nonlinearity provided by the thousands of outer hair cells. However, attempts to replicate cochlear function via sound processing thus far have met with negative effects (as discussed in Moore, 1996), likely due to artifacts introduced by the processing (Edwards, 2004).

Acoustic Effects of Compression

Spectral Changes

The main spectral change caused by WDRC is an increase in audibility across a wider frequency range than is possible with linear amplification. In general, more extreme WDRC has the effect of reducing spectral contrasts, particularly as more channels of compression are used (Dreschler, 1993; Westermann, 1993). Spectral smearing reduces information important for vowel identification and place of articulation information. For only one or two channels of compression, the negative consequences in the spectral domain are somewhat minimal; beyond that, spectral information in complex signals is reduced predictably as the number of compression channels increases (Moore, 1996).

Temporal Changes

Compression has its greatest negative effect upon the temporal envelope of speech, an acoustic dimension that carries important speech information (Van Tasell, 1993). Evidence for the importance of the temporal envelope comes from experiments in which a noise carrier is modulated by the speech envelope and listeners are able to reach a good level of performance, suggesting that the envelope provides cues to speech identification (e.g., Shannon, Zeng, & Wygonski, 1992; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995; Turner, Souza, & Forget, 1995; e.g., Van Tasell, Greenfield, Logemann, & Nelson, 1992; Van Tasell, Soli, Kirby, & Widin, 1987).

The specific information carried by the temporal envelope includes segmental cues to voicing, manner of articulation, and prosodic cues for tempo, rhythm, and syllabicity for understanding speech in quiet (Rosen, 1989). In the processing of speech in noisy environments, the temporal envelope may have a role in sound source segregation (Crouzet & Ainsworth, 2001, 2001). When the temporal envelope is smeared, recognition in noise gets worse. This effect is even greater when the background is a modulated noise.

For both normal-hearing and hearing-impaired listeners listening to spectrally-degraded speech in noise, expansion of the temporal envelope leads to faster reaction times. If reaction time can be assumed to be associated with ease of listening, as is commonly thought (e.g., Bashore et al., 1997; Cohen & Faulkner, 1983; Gatehouse & Gordon, 1990), then enhancement of the temporal envelope may provide additional information that contributes to ease of listening (Apoux, Crouzet, & Lorenzi, 2001).

Taken together, all of these results show that the temporal envelope carries important information that can be used in speech processing. As discussed earlier, as hearing loss increases, frequency resolution becomes poorer, resulting in a greater reliance on the temporal envelope (e.g., Faulkner, Ball, Rosen, Moore, & Fourcin, 1992).

As the time constants of compression are made shorter, the effect on the temporal envelope increases. Specifically, shorter time constants lead to a smoothing of the envelope, such that any level differences that the listener may use to help understand the speech signal are no longer available (Van Tasell, 1993). Multiple studies provide evidence that fast-acting compression affects the temporal cues in speech (e.g., Boothroyd, Springer, Smith, & Schulman, 1988; Dreschler, 1989; Festen, van Dijkhuizen, & Plomp, 1990; Plomp, 1988; Verschuure et al., 1996).

What are the consequences of changing the envelope on speech recognition? Not much effect is found when there is redundancy in the signal, when undistorted speech is presented in quiet, or when the listeners are younger or have normal hearing (Rosen, Faulkner, & Reeve, 1994; Shannon, 2002). Under these listening conditions, there is sufficient redundancy in the signal that the listener can extract the information from the speech signal without needing the added information provided by the temporal envelope.

When the inherent redundancy in the speech signal is reduced by removing most of the spectral information, leaving only temporal cues, then fast-acting WDRC has been shown to reduce recognition for the speech material (Souza, 2000; Souza & Kitch, 2001; Souza & Turner, 1996, 1998; Van Tasell & Trine, 1996). Fast-acting compression has also been shown to reduce speech quality ratings, even in the absence of changes to objective speech recognition measures (van Buuren, Festen, & Houtgast, 1999).

However, one might ask what the effect of altering the temporal envelope is when the listener has access to full spectral cues. Jenstad and Souza (2005) found that, for recognition of nonsense syllables in quiet, changes to the temporal envelope accounted for 6% of the variance in reduced benefit from compression. This was a small but significant amount of the variance accounted for, on a speech task in which the listeners had full access to the spectral information, suggesting that even for this type of task, acoustic alterations caused by compression have a detrimental effect for hearing-impaired listeners.

Aging and WDRC

Given the acoustic changes caused by WDRC and the perceptual deficits of older adults, including temporal processing deficits and difficulties with complex listening situations, one might expect that older adults would have difficulties recognizing speech processed with WDRC, particularly as the compression parameters are changed to create greater alterations to the temporal envelope. This has not been the case in the research literature.

Souza, in several studies, has shown that, under some circumstances, alteration of the temporal envelope does not have a greater effect for older than younger listeners (Souza, 2000; Souza & Kitch, 2001). The age effect in these studies was apparent in all conditions, not just those in which the envelope was altered by WDRC. It seemed that the older listeners did not use the information contained in the temporal envelope as much as younger listeners, even when the envelope was intact.

In previous research on the effects of WDRC on speech recognition, no emphasis has been placed on testing the performance specifically of old-old listeners. Often the age of listeners has not been specified at all (e.g., Crain & Yund, 1995), making it impossible to interpret the results for individual age groups. In other studies, a wide range of ages, such as 30 to 90 years, has been tested without examining individual variability by age (e.g., Gatehouse, Naylor, & Elberling, 2003; Larson et al., 2002; Olsen, Olofsson, & Hagerman, 2004; van Toor & Verschuure, 2002). Several of these studies have shown slight benefit or detriment, or little effect at all. Again, without examining the age-related changes in benefit, it is difficult to know whether there were in fact large individual differences that averaged together to create a small overall effect. In other studies, older listeners have been restricted to the young-old group (e.g., Nabelek, 1983; Verschuure, Benning, Van Cappellen, Dreschler, & Boeremans, 1998). Both Nabelek and Verschuure found that fast-acting compression was beneficial for most of their listeners, but both limited subject selection to listeners under the age of 70 years. This restricted range of listeners is not representative of the age-related changes that occur for old-old adults.

In summary, the results of all these studies have shown that, contrary to expectations, older adults do not seem to be susceptible to the distortions of WDRC processing. It is possible that no age effect has been shown for certain types of compression because older adults are *not* more susceptible to compression-induced distortion, but it is more likely that either there is an acoustic reason for the lack of effect, or the older listeners are using one or more compensatory mechanisms to recognize speech under these degraded listening conditions, or that the older listeners tested to date have not been in the old-old age group.

Acoustic Hypothesis

The lack of effect related to acoustic characteristics of WDRC processing is related to the question of how much the temporal envelope is really altered by WDRC. Often WDRC characteristics are measured with tones that are amplitude-modulated at a slow rate, allowing the compressor to fully reach its steady-state compression. This does not effectively characterize WDRC processing for signals such as rapidly changing speech or speech in background noise. Measures of compression characteristics using tones tend to overestimate the actual compressive effect for rapidly changing speech (Stone & Moore, 1992). In addition, there is evidence that compression parameters interact with one another in creating the acoustic effect. Therefore, if we are to examine the effects of distortion caused by WDRC, it will be important to have a way to quantify the acoustic changes, rather than relying on nominal parameter settings. Several methods have been tried.

Methods of Quantifying WDRC Acoustic Changes

Speech Transmission Index

It has been thought that the Speech Transmission Index (STI) would be a good model to account for the changes in speech recognition for compression hearing aids because the model was designed to account for alterations to the temporal envelope. The

STI is a measure of how well a system preserves the temporal modulation of speech. Predictions of speech intelligibility are based on how well preserved, or conversely how distorted, the speech signal is. The model compares a well-defined input to the output of a system (Humes, 1993), where the system can be a reverberant room or a compression hearing aid, for example. The aim is to quantify how distorted speech is.

The STI is based on measurement of the modulation transfer function (MTF), which quantifies how much an input signal is changed by a system. The input stimulus is a speech-weighted noise, 100% modulated at different modulation frequencies typically found in speech. The output is the modulation depth at each frequency for the same modulated noise after it has been processed by the system under investigation. The MTF shows how much modulation is lost by the system as a function of input modulation frequency (Humes, 1993). The MTF is measured for each of the modulation frequencies in octave bands through the speech range. The change in modulation depth is converted to an equivalent signal to noise ratio; that is, how much noise would be required to fill in the gaps in the input modulated signal to produce the output signal. Within each octave band, the average of SNRs (that is, averaged across all the modulation frequencies) is taken. The values from each frequency band are combined through a weighted averaging to provide a single number index of the system's effects on an acoustic signal.

There is some evidence to show that the STI is able to predict speech recognition in noise, reverberation, or with amplitude compression because these effects are explicitly measured and included in the model. For instance, Humes, Dirks, et al., (1986) tested normal hearing listeners under conditions of reverberation and found that the STI was a good descriptor of the listeners' word recognition performance.

However, it has also been shown that the STI has shortcomings for characterizing the effects of amplitude compression in hearing aids. Drullman (1995) assessed the STI for quantifying audibility with compression hearing aids. He manipulated the signal in two ways that would have low predicted speech recognition according to the STI. In the first manipulation, he filled troughs of speech with noise, which would reduce the measured modulations. In the second manipulation, he reduced the amplitude peaks in a manner similar to wide-dynamic range compression. In fact, actual measured speech recognition was high for both conditions, and was higher for the amplitude reduction than noise, whereas the STI would have predicted low and equivalent scores in the two conditions. Hohmann & Kollmeier (1995) had similar results to Drullman. They created a compression system that the STI would predict to have maximum degradation of speech intelligibility. In fact, there was little change in speech intelligibility despite a reduction in speech quality.

It has been proposed (e.g., Ludvigsen, Elberling, Keidser, & Poulsen, 1990; Payton & Braida, 1999) that use of real speech rather than modulated noise to define the transfer function of the compression system would improve the predictive ability of the model. A major barrier to the use of real speech has been that it introduces artifacts at high modulation frequencies, which makes it appear as if the system is preserving those modulations when it fact it may be not transmitting them properly (Payton & Braida, 1999).

For the purposes of the current study, the STI approach has several drawbacks: it is difficult to implement with real speech, it requires measurement of a long segment, and it is not accepted for use with compression-amplified signals.

EDI

An alternative method for quantifying WDRC distortion is the Envelope Difference Index (EDI: Fortune, Woodruff, & Preves, 1994). The EDI uses an envelope subtraction technique to provide a single index quantifying the difference between two temporal envelopes. The calculation can be applied to real speech samples of any length and was developed specifically for use on compression-amplified signals. Briefly, the procedure involves obtaining the temporal envelope of two signals and calculating the difference between them on a scale from 0 to 1, with 0 representing complete correspondence between the waveforms and 1 representing no correspondence between the waveforms. The advantages of the EDI compared to the STI are that it uses a real speech signal and it only quantifies the changes likely to be caused by compression, thereby avoiding the problem with the high frequency temporal modulations. Figure 2 shows an example of the EDI for the nonsense syllable /ip/, where the calculated EDI is .14. (Figure 2)

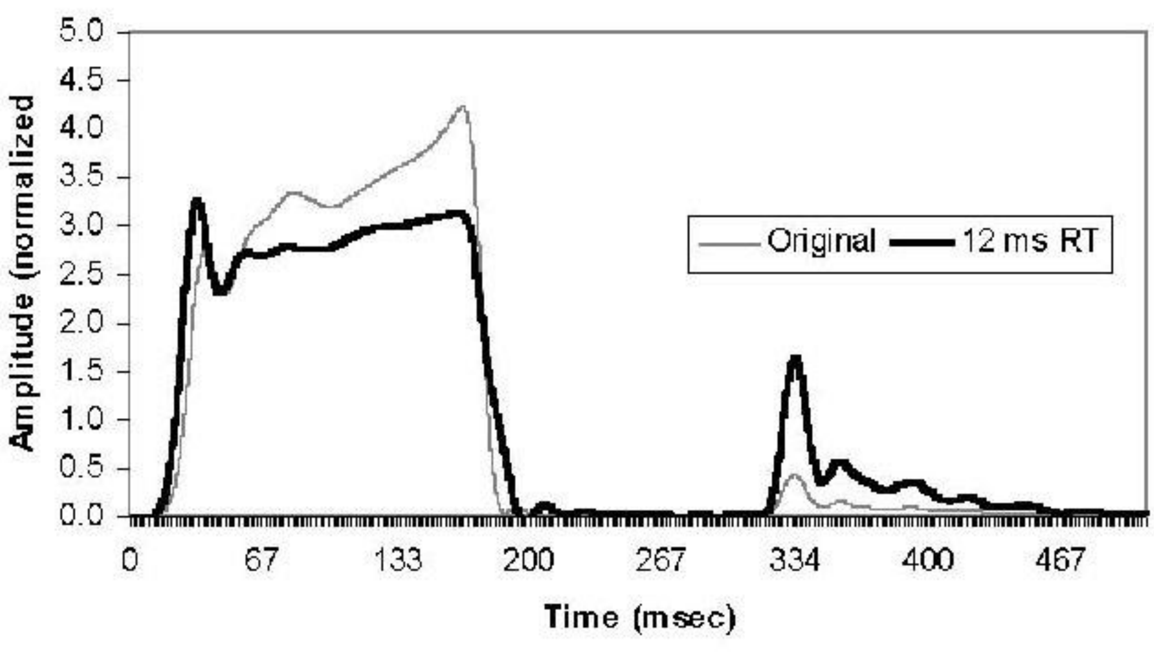

Figure 2. An example calculation of the Envelope Difference Index (EDI) for the syllable /ip/ at the 65 dB SPL input level. The thin line is the normalized amplitude envelope for the unprocessed syllable and the thick line is the normalized amplitude envelope for the syllable. The EDI value for the difference between these two envelopes is .14.

Acoustic Effects of Compression Parameters

We have conducted several studies in our laboratory on the acoustic effects of WDRC processing, using the EDI tool. Our results show that the amount of alteration to the speech caused by WDRC processing depends upon several factors: the specific compression parameters, the combinations of parameters, and characteristics of the input signals.

Release Time as a Function of Input Level

Jenstad and Souza (2005) quantified the effects of release time on the temporal cues in speech and found that the effect of release time interacted with the input level to the compressor. We used two measurements: the consonant-vowel ratio (CVR) that measures the level differences between neighboring consonants and vowels, and the Envelope Difference Index (EDI) (Fortune et al., 1994) that reduces the differences between two envelopes to a single number. Both of these measurements showed significant effects of release time on the temporal cues of speech: shorter release times led to greater differences of the envelope. This effect was dependent upon the input level to the hearing aid; that is, the level of the speech relative to the compression threshold of the instrument. As the level increased above compression threshold, the effects of the shorter release times were greater. Figure 3 shows the EDI results for the three release times at the three input levels to the compressor. This figure shows the interaction between release time and input level to the compressor. For the shortest release time, as input level increased, the resulting EDI value increased. For the longest release time (800 ms), input level had very little effect on the resulting EDI value. At the lowest input level (50 dB SPL), there were no meaningful differences among the release times in terms of their effect upon the temporal envelope. (Figure 3)

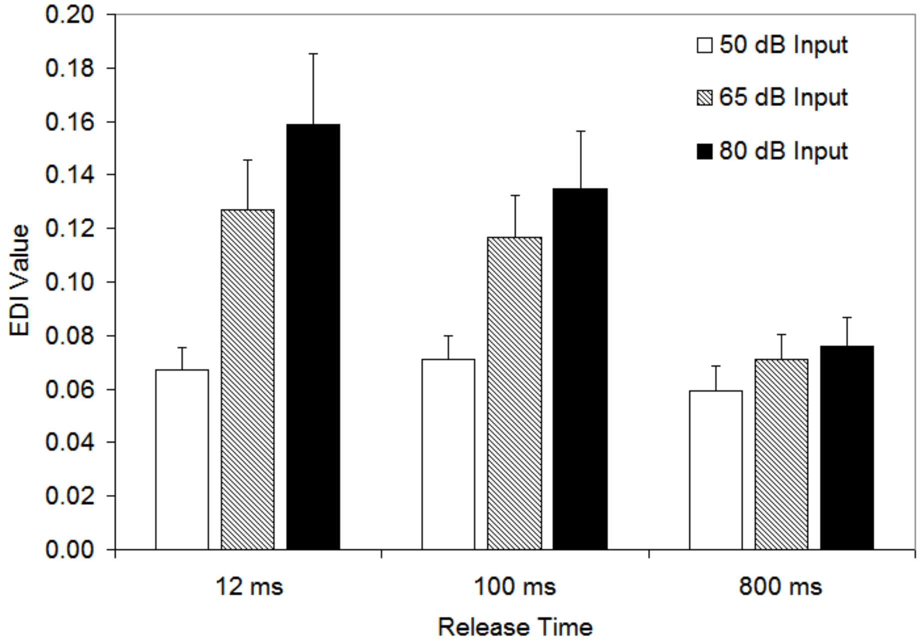

Figure 3. EDI values for three release times (12, 100, and 800 ms) as a function of input level to the compressor.

Release Time and Compression Ratio

The effect of release time also interacts with other compression parameters, such as the compression ratio (Jenstad & Souza, 2004). We quantified this effect also using the EDI measurement. At low compression ratios (e.g., 2:1), the effect of release time is quite small. At higher compression ratios (e.g., 4:1, 10:1), the effect of shorter release times is greater. Figure 4 illustrates this interaction between compression ratio and release time. From the graph it is clear that at the 2:1 compression ratio, changing release time drastically has little effect on the temporal envelope. (Figure 4)

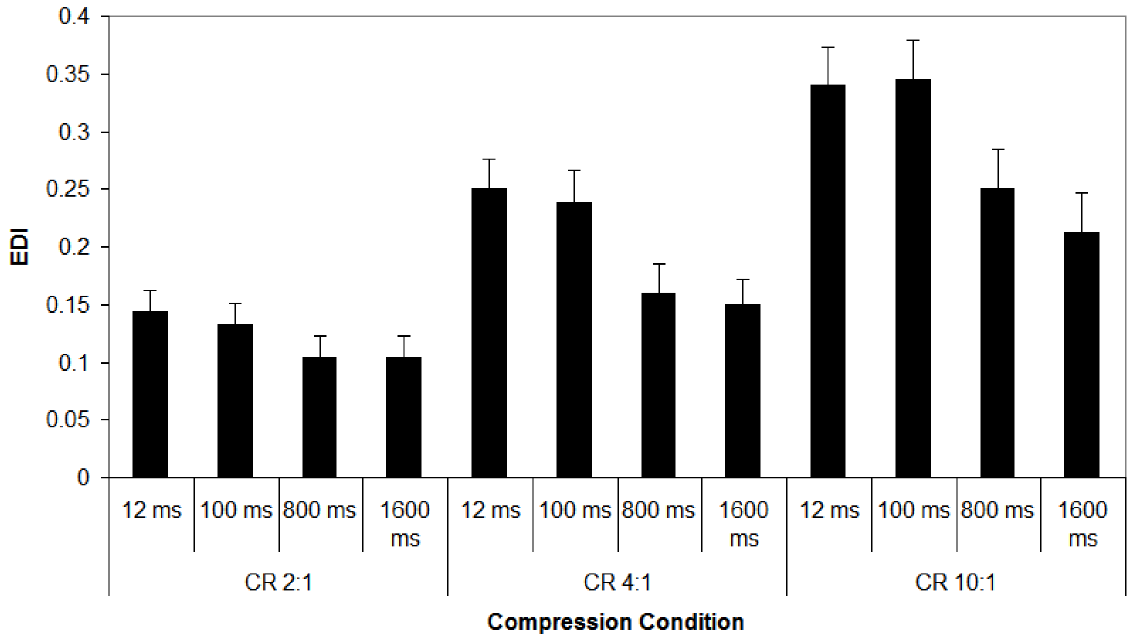

Figure 4. EDI values for four different release times (12, 100, 800, and 1600 ms) as a function of compression ratio.

This finding has important consequences when interpreting behavioral results of compression comparisons. If the behavioral effect of release time is studied at only a low compression ratio, then our acoustic results show that one would not expect to actually find a large behavioral effect. For example, Bentler and Nelson (1997), compared four release time settings (ranging from 20 to 500 ms) and found no differences among them for intelligibility or preference. The exact compression ratio was not specified, but the hearing aid used curvilinear compression, which tends to be characterized by quite low compression ratios. On the other hand, comparisons of release times at a larger compression ratio have a greater acoustic effect, and so might be expected to result in a greater behavioral effect, as has been found in several studies (e.g., Neuman, Bakke, Mackersie, Hellman, & Levitt, 1998; e.g., Olsen et al., 2004).

Similarly, comparisons made between different compression ratios, if made with only long release times, would show little effect (e.g., Neuman et al., 1998). Studies that have compared compression ratios at short release times, where acoustic effects would be expected to be quite different, have shown significant declines in recognition as compression ratio increased (Boike & Souza, 2000; De Gennaro et al., 1986; Souza & Kitch, 2001).

Altogether, the acoustic results of compression for real speech point to the need for quantifying the acoustic effects of the compression system under study in any particular behavioral study. The specific compression parameters interact with one another and the actual acoustic effect changes with compression settings used. It would not be reasonable to expect behavioral differences for conditions that are very similar acoustically.

Compression Parameters and Background Noise

Given that older adults are more susceptible than younger adults to the effects of background noise, particularly at poor signal-to-noise ratios (Gordon-Salant & Fitzgibbons, 1995), when the noise is interrupted or modulated (Stuart & Phillips, 1996; Turner et al., 1995), and when the background noise is meaningful (Tun et al., 2002; Tun & Wingfield, 1999), it might be expected that the combination of WDRC and noise would lead to greater reduction in speech recognition due to the combination of signal distortions. However, recent work in our laboratory on the acoustic effects of compression has shown that when compression is applied to speech in background noise, the acoustic compressive effect all but disappears (Souza, Jenstad, & Boike, submitted). For example, the effective compression ratio is lower and the temporal envelope of speech is barely altered in noise. Figure 5 shows the EDI values in quiet again, as shown in Figure 4, along with the EDI values for sentences compressed in background noise. The EDI values are smaller in the noise condition, indicating less change to the temporal envelope. This effect is seen across a range of signal to noise ratios, and for both steady noise and multi-talker babble. Thus, compression of speech in noise would not be expected to have a greater effect on recognition than background noise with uncompressed speech. (Figure 5). Indeed, previous research that has compared compression settings for speech recognition in backgrounds of steady or slightly modulated noise has indeed shown very small behavioral differences among compression types (Bentler & Nelson, 1997; Gatehouse et al., 2003; Moore, Stainsby, Alcantara, & Kuhnel, 2004; Sammeth, Tetzeli, & Marleen, 1996; Verschuure et al., 1998).

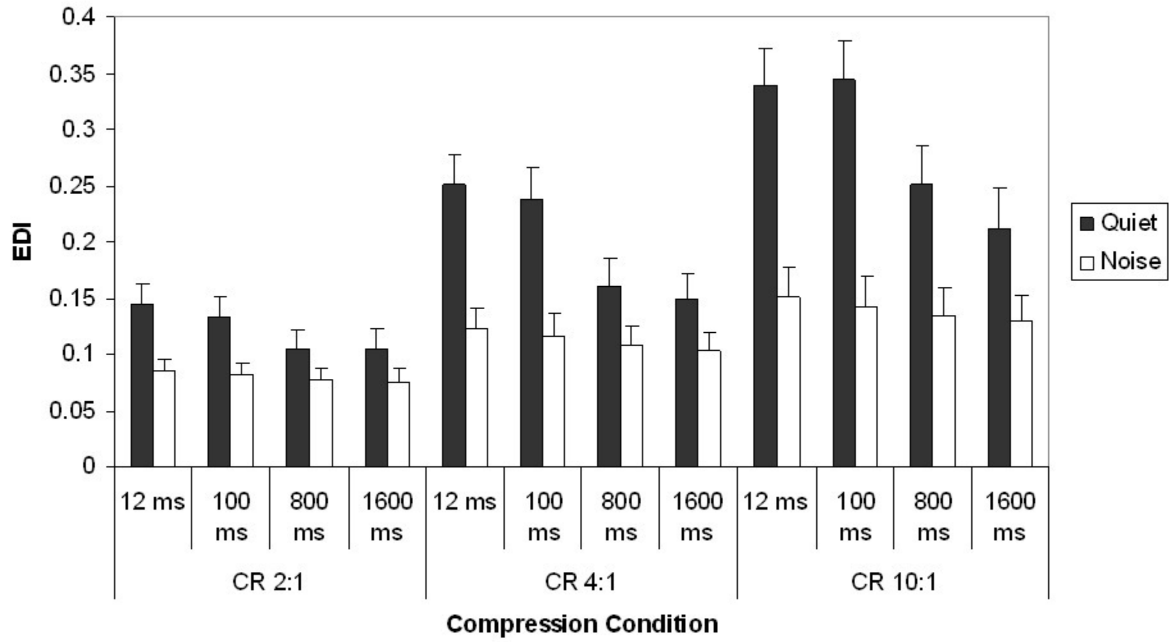

Figure 5. EDI values for speech compressed in quiet or in a background of 12-talker babble.

Listening Strategy Hypothesis

The previous discussion was aimed at explaining the lack of behavioral compression effect by examining the characteristics of compression processing itself. The results showed that the acoustic effect of compression processing depended upon the combination of parameters chosen and the presence or absence of background noise.

In addition to the nature of WDRC processing, there may also be effects related to the listener's strategies. Earlier I alluded to the connection between peripheral and cognitive processes as a strength for compensating for a degraded signal. It has been shown that older listeners are at least as good as, if not better than younger listeners, at using higher-level resources to compensate for listening to a distorted signal. Let us examine this process in more detail.

Most current models of spoken word recognition are based on the consensus that two fundamental processes are involved in speech recognition: first, an acoustic input activates lexical items in memory; second, the listener discriminates among the activated items (Auer, 2003; Jusczyk & Luce, 2002; Luce & McLennan, 2003; Luce & Pisoni, 1998). The acoustic phonetic patterns are the primary source of information used to activate the lexical candidates. Additional candidates are provided from the semantic and syntactic context (Salasoo & Pisoni, 1985). Gating experiments, in which successively greater portions of a word are presented (e.g., the first 10 ms, the first 20 ms, etc) are sometimes used to determine how much of the signal needs to be presented before the listener can recognize the word. In continuous discourse, only the first half, or even less, of a word needs to be presented acoustically for the word to be recognized; the remainder can be inferred from higher-level knowledge sources when context is available (Marslen-Wilson & Tyler, 1980). The balance between knowledge sources (acoustic input and prior linguistic experience) allow the listener to understand the speech even when there is uncertainty due to signal degradation, from factors such as the presence of background noise or hearing loss.

Perceptual and Cognitive Processes

In understanding speech, both the perceptual and cognitive processes are used and these processes are interdependent. The importance of the cognitive process in decoding the signal depends upon the amount of degradation to the acoustic signal. If the input signal is degraded acoustically in some way, the signal becomes uncertain. An uncertain acoustic signal is thought to activate more lexical candidates than a clear signal. For example, if the relative amplitude and spectral cues of the word "dog" are degraded, then the place of articulation of the initial sound is uncertain. Instead of only words beginning with /d/ being activated, words beginning with /b/ or /g/ may also be activated. This in turn leads to greater demands on cognitive processing, as the listener must choose among more activated candidates, which either leads to greater processing time or more errors in recognition. Older adults have retained, and even enhanced, their ability to use linguistic knowledge to assist with cognitive processing of the signal. However, if the task removes the support available in the cognitive domain, by reducing the linguistic context, increasing the length of the utterance, or reducing the processing time, listeners are more dependent upon the acoustic signal.

Top-Down Compensation for Peripheral Degradation

Context

In older listeners, some higher-level linguistic skills are retained or even enhanced, such as use of prosody, syntactic knowledge, vocabulary size, and use of context. When sufficient linguistic context is provided to older listeners, it has been shown that they can take advantage of the context to fill in the information lost due to signal degradation. In fact, the majority of research on the use of context by elderly listeners has shown that they receive greater benefit from additional context than do younger listeners. Under these circumstances, the age effect due to a complex listening task or signal degradation may be minimized.

Nittrouer and Boothroyd (1990) tested a model of the benefit from context with older adults, aged 62 – 82 years, with normal hearing status for their age. The speech materials included real and nonsense words, meaningful and meaningless sentences, and both words and sentences of varying degrees of predictability from context. As expected, there was a significant age effect on all of the materials: older adults had lower recognition scores than younger adults for phonemes, words, and sentences. However, the benefit on phoneme recognition from real words compared to nonsense words was greater for older adults than younger adults.

The apparent enhanced context effect for older listeners extends beyond just the word/ non-word distinction. Pichora-Fuller, Schneider and Daneman (1995) also found that older listeners made better use of context than younger listeners when the task was identifying sentence-final real words in either a highly predictable or an unpredictable context. Again, the seemingly better use of context by elderly listeners was due to lower scores than the young listeners for the low context words and equivalent scores between the two age groups for the high context words. Taken together with similar results from Sommers and Danielson (1999) and Dirks, Takayanagi, Moshfegh, Noffsinger, and Fausti (2001), there is evidence that the semantic information in high-predictability sentences is beneficial for older listeners when trying to understand words in difficult listening tasks.

The context effect is also found for closed-set tasks versus open-set tasks. For a closed-set task, even nonsense syllables become highly predictable during the specific speech recognition task (Boothroyd, 1993; Sommers, Kirk, & Pisoni, 1997). This effect goes beyond simply changing the chance level due to guessing.

For listening tasks in which undistorted speech is presented in quiet or steady-state noise, it can be shown that older listeners do not appear to receive greater benefit from context. Dubno, Ahlstrom, and Horwitz (2000) performed another test of older listeners' use of context in understanding a sentence-final word while controlling for audibility differences with low-level steady-state noise. The 50% point of the performance-intensity function was compared between the two age groups, ensuring that the perceptual difficulty was the same for both groups. The slope and threshold of the performance intensity function were shifted between the low-context and the high-context sentences. The changes in the function were the same for the two age groups, leading the authors to conclude that once the effects of audibility are accounted for with equivalent background noise, older listeners receive the same benefit from context as younger listeners.

For complex speech perception tasks, such as for modulated background noise, reduced audibility, or a distorted speech signal, in which the acoustic signal is degraded, older listeners rely more on any available top-down information that can help them to understand the signal. Performance was degraded for older listeners only in difficult listening situations without semantic context. Therefore, older listeners appear to make greater use of context to understand acoustically *uncertain* speech.

Thus, the nature of the age effect observed can be highly dependent upon the type of speech stimulus used. If speech that is highly predictable from context is presented, even multiple degradations may not result in a measurable age effect, leading one to conclude that speech recognition skills do not change with age. However, for speech that is not predictable, such as a monosyllabic word in a carrier phrase, or the low-probability sentences of the Speech in Noise Test (SPIN test), listeners will be forced to rely more upon the acoustic signal input to understand the message. Such unpredictable speech is more susceptible to the effects of acoustic degradation (Gordon-Salant & Fitzgibbons, 1997).

In order to isolate the peripheral and cognitive influences on speech recognition, it will be important to control for context. One solution has been to use relatively context-free speech, such as nonsense syllables. There are two potential problems with using short nonsense syllables to study complex speech recognition. First, without a large set of nonsense syllables available for testing, listeners can learn the particular characteristics of the tokens being tested, leading to practice effects that are relevant only to that stimulus set (Van Tasell et al., 1992). With this type of small set design, it is unknown which cues of speech are being used by the listener and whether these cues could generalize to other talkers. Second, the acoustic cues used to identify nonsense syllables are different from the acoustic cues used to identify sentences. For example, Van Tasell and Trine (1996), found that listeners with normal hearing identifying words and sentences with all spectral information removed had different listening strategies for each speech type; for nonsense words, the listeners used the temporal envelope, periodicity, and stimulus artifacts to identify the word; for sentences, the listeners used only the temporal envelope. This distinction in acoustic cues used for recognition becomes particularly important in complex listening conditions in which some types of acoustic cues are degraded. According to the Van Tasell and Trine results, alteration of the temporal envelope has a greater effect for sentence material than nonsense syllables because listeners can use other cues to identify nonsense syllables when temporal envelope information is altered.

Because nonsense syllables are not the best way to isolate peripheral effects during complex speech recognition, other methods will be necessary to try to separate the contributions of peripheral and central damage on speech recognition. A well-studied test of context effects is the Speech Perception in Noise test (SPIN; Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984), in which sentences are used that control the linguistic context available.

The well-documented context effect has implications for interpreting results of WDRC studies. Have older adults been using context to compensate for the distorted signal? Testing a potentially distorted listening condition such as WDRC with highly predictable speech may lead to the conclusion that WDRC is not detrimental. When other types of temporal distortion, such as reverberation or time-compression, are added to a speech signal, recognition remains fairly high as long as contextual cues are available (Gordon-Salant & Fitzgibbons, 1997)

In the few studies that have specifically examined the benefit older listeners receive from WDRC processing, context has been available in the form of closed-set tasks. For example, Souza and Kitch (2001) tested older adults' ability to understand sentences processed with compression amplification. Older adults had poorer speech recognition than younger adults for all conditions, regardless of the amount of compression applied, which seemed to imply that older adults were not more vulnerable to compression amplification (across a restricted range of distortion values). However, the speech recognition task was a closed-set test. This task variable may have helped the older listeners in the most difficult listening conditions. Similarly, Souza (2000), tested older adults' ability to understand syllables with WDRC amplification, again a closed-set task, and showed that the older listeners with hearing loss were not more susceptible to the negative effects of WDRC processing than younger listeners.[2]

Processing Time and Acoustic Redundancy

Other mechanisms that older listeners may be using to achieve the same speech recognition as younger listeners are increased processing time or acoustic redundancy within the signal. Rapid speech can be used to test both of these hypotheses and to separate them by using time-compressed plus time-restored listening conditions. The effects of time-compression on speech recognition for older listeners are well-documented in the literature. Interactions of time-compression and other temporal distortions, such as reverberation or modulated background noise, are also well-studied for this population. The interaction is such that the combination of two temporal distortions is more detrimental to recognition than the simple combination of distortions would predict. Acoustic analyses have not been done to ensure that the interaction is truly occurring with the listener rather than at the acoustic level, such as the interaction between WDRC and background noise.

Although time-compressed speech has been well-studied, the interaction between time-compressed speech and the temporal distortion of WDRC has not been studied. A behavioral interaction between these two listening conditions would indicate that when only WDRC is presented, older listeners must be using a compensatory mechanism in their recognition of this single-distortion speech. The time-compressed speech must be reducing the listener's ability to compensate for the WDRC distortion. The nature of the compensatory mechanism can be understood by comparing the results of time-restored and time-compressed speech. These two speech conditions have the same amount of acoustic information, but the time-restored condition replaces the time removed by the time-compression processing. If the scores do not improve when time is restored to the time-compressed signal, it indicates that the listener has been using acoustic redundancy. If the score in the time-restored condition improves, it indicates that the listener has been using increased processing time to compensate for WDRC distortion.

Summary and Experimental Questions

The focus of the current research study was to determine whether older adults use compensatory mechanisms when listening to speech in which the temporal envelope has been altered by WDRC processing. To best isolate the listening mechanisms older adults

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[2] Note, however, that the results of this study showed that the older listeners with *normal* hearing had worse recognition with WDRC processing than linear processing, perhaps providing evidence for an age-related susceptibility to temporal envelope alteration.

may use to recognize WDRC speech, the following considerations were taken in the experimental design. First, low-context sentences from the SPIN test were used, to reduce as much as possible the contributions of higher-level compensation. Second, acoustic measurements of each compression condition were made to ensure there were measurable acoustic differences between the WDRC conditions tested, but no acoustic interaction between WDRC and speech rate. These measurements were made on the EDI scale, allowing for quantification of temporal envelope changes that are not linked to specific compression parameters. Third, old-old listeners (75+ years) were compared to young-old listeners (<74 years). Based on previous research of complex speech recognition, an age effect was expected between these two groups. This design allowed for better control over hearing loss factors. Listeners younger than 60 years were not recruited for the current study in an effort to not have hearing loss and age as confounds. Much of the previous research on aging has had difficulty separating the effects of age and hearing loss (but for notable exceptions, see Dubno et al., 2002; Dubno et al., 1997; Studebaker et al., 1997). A typical design recruits participants in four groups: young listeners with normal hearing, young listeners with hearing loss, old listeners with normal hearing, and old listeners with hearing loss. It is generally thought that by comparing young and old listeners with the same hearing status the age effect can be quantified. There are three main difficulties with this design. First, the "normal" hearing old listeners usually have worse thresholds than the normal hearing young listeners. This arises because the definition of normal hearing is so broad. It is possible, for example, to have a 25 dB average difference between these two groups and still have them both classified as normal. Second, the question arises of whether the normal-hearing old listeners are truly representative of the aging population. The third difficulty is that the hearing loss of the young listeners is typically of different etiology, degree, and configuration than the old listeners. Thus, listeners from 60 to 90 years with similar hearing losses were recruited for this study.

Given that some types of wide-dynamic range compression alter the temporal envelope and these alterations have been related to reduced speech recognition benefit

(Jenstad & Souza, 2005), will these alterations result in reduced speech recognition for older listeners when the listening task is designed to reduce their access to compensatory mechanisms? Specifically, when WDRC is combined with rapid speech and the support of a predictable linguistic context is controlled, does WDRC interfere with speech recognition for older adults?

Experimental Questions

1. ***As WDRC distortion increases (as quantified on the EDI scale), is it detrimental to recognition of low-context sentences?***
2. ***As WDRC distortion increases (as quantified on the EDI scale), is it detrimental to recognition of low-context time-compressed speech?***
3. ***Is the pattern different for time-compressed and normal rate speech?***
4. ***How do these effects change across age groups?***
5. ***Is the rapid speech effect consistent with reduced acoustic redundancy or reduced processing time?***

Method

Participants

Participants were 6 male and 19 female adults, 11 young-old listeners (62 to 74 yrs) and 14 old-old listeners (75 to 88 yrs)[3]. The two age groups were matched for hearing levels (moderate to moderately-severe sloping sensorineural loss), and all subjects had results consistent with normal middle ear on tympanometry, and air and bone conduction thresholds. The mean audiograms are shown in Figure 6. (Figure 6)

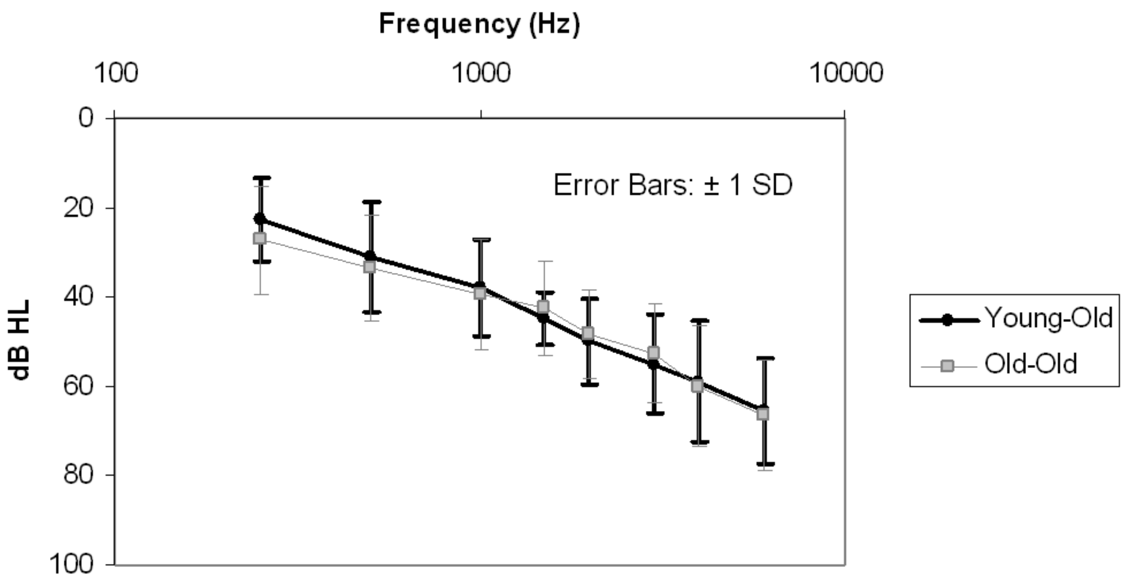

Figure 6. The average audiograms for the young-old (age 62-74 yrs) and the old-old (age 75-88 yrs) participants. Error bars represent 1 standard deviation.

Participants were screened for general health status using a self-report scale, for cognitive disorders using the Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975), and for short-term memory deficits using the digit span subtest of the Wechsler Memory Scale (Wechsler, 1972). Scores on the self-report scale ranged from 4 – 7 (where 7 was the highest score). Scores on the MMSE ranged from 23 to 30 (where 30 was the

[3] Based on pilot data, a minimum of eight subjects per group was required for power of at least .83 for each comparison of interest.

maximum score). Scores on the digit span test ranged from 9 to 15 (where 15 was the maximum score). If subjects were current hearing aid wearers, information about the hearing aid type and usage was recorded. Paired comparisons showed that the two age groups did not differ on any of these demographic variables with an alpha of .05 [MMSE: $t(23) = .929$, $p = .362$; Digit Span: $t(23) = .990$, $p = .333$; Health: $t(23) = .595$, $p = .558$]. The means and standard deviations for the two groups on these measures are shown in Figure 7. (Figure 7)Table 1 gives the scores for individual participants on the MMSE, digit span test, and health rating. Pure-tone thresholds and hearing aid history are in Table 2. All participants were compensated for their time and travel expenses.

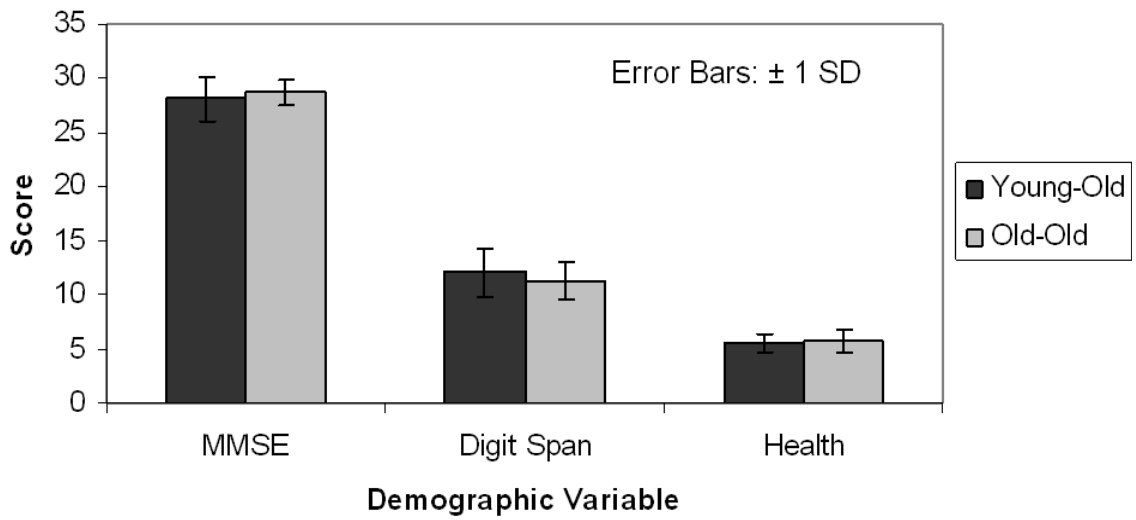

Figure 7. The means and standard deviations for the two groups of participants (young-old and old-old) on the MMSE and digit span tests, and the health-related quality of life self-rating. The groups did not differ on any of these measures.

Two participants in the old-old group could only complete the normal rate condition. Despite extensive practice and training on the time-compressed condition, they could not perform the speech recognition task for the rapid condition. These two participants did not have any distinguishing characteristics on the screening tests: they were not the two oldest participants, they did not have the greatest degree of hearing loss, and they did not have low scores on the cognitive screening, digit span, or health rating.

Table 1. Age, sex, and scores on the Mini-Mental State Exam (MMSE), Digit Span of Wechsler Memory Scale, and self-reported health rating for each participant.

Subject ID	Age (yrs)	Sex	MMSE	Digit Span	Health Rating
101	71	F	27	11	4
102	71	F	30	9	7
103	62	F	29	15	6
104	70	F	27	9	5
105	73	M	29	12	6
106	67	F	28	15	6
107	73	F	30	15	6
108	71	F	23	11	6
109	67	M	27	13	6
110	64	F	29	13	5
111	73	F	30	10	4
201	78	M	30	12	5
202	82	M	30	9	6
203	83	F	27	10	4
204	79	M	28	13	5
205	75	F	30	13	6
206	80	F	28	9	6
207	80	F	30	12	6
208	80	F	30	14	7
209	76	F	27	11	7
210	86	F	27	11	6
211	88	F	28	9	4
212	84	F	28	14	7
213	75	M	30	10	5
214	77	F	29	11	7

Table 2. Hearing aid history and pure-tone thresholds (dB HL) for each participant.

Subject ID	HA History	250	500	1000	1500	2000	3000	4000	6000
101	>5 yrs, bin., WDRC	30	40	50	50	50	50	55	55
102	N	15	50	35	50	50	55	55	65
103	N	25	30	40	40	40	40	40	40
104	N	40	40	50	45	40	50	50	65
105	3 mo, bin, WDRC	25	40	35	40	45	60	65	75
106	N	15	20	20	40	50	75	90	85
107	N	20	35	35	35	35	35	45	60
108	N	20	15	30	55	55	55	55	75
109	N	5	10	40	45	65	65	65	60
110	>5 yrs, bin., WDRC	30	35	55	50	65	60	60	70
111	N	25	25	25	45	55	60	70	70
201	>5 yrs, bin., *info N/A*	15	25	35	40	45	60	65	65
202	N	30	40	45	45	60	70	80	80
203	N	40	45	45	50	50	55	65	70
204	>5 yrs, L ear, lin	35	30	40	55	65	70	75	80
205	2 mo, bin., WDRC	25	30	30	35	40	45	70	95
206	2 yrs, bin., WDRC	40	35	40	45	45	55	70	65
207	2 yrs, R ear, WDRC	20	40	40	40	45	55	60	60
208	>5 yrs, bin., *info N/A*	30	40	45	50	55	60	70	65
209	N	15	25	40	40	40	35	50	45
210	N	20	25	40	45	45	45	35	60
211	15 yrs, bin., WDRC	55	65	75	65	65	60	65	65
212	N	15	20	25	30	45	40	45	50
213	N	25	25	30	25	45	45	45	65
214	N	15	25	25	30	30	40	45	65

Stimuli

Stimuli were the sentence materials from the Speech Perception in Noise (SPIN; Bilger et al., 1984) test. In this test, the final word is either highly predictable from context or not at all predictable from context. An example of a high probability sentence is “Zebras have black and white stripes,” in which many semantic cues contribute to the predictability of the final word. An example of the same word in a low probability sentence is “They were talking about the stripes.” In the low probability sentences, correct syntactic structure is retained, but no semantic cues for the final word are given. To control for contextual factors, only the low probability sentences were used for test stimuli.

The SPIN test consists of 8 lists with 25 low-probability sentences per list. Each sentence consists of three to six key words (pronouns, nouns, verbs, adverbs, adjectives). Because of the variability in the number of key words, each list had a different total number of key words to be scored. The number of key words ranged from 110 to 127 words across the 8 lists (mean = 119.1 words, SD = 5.3). The 8 lists of low-probability sentences are shown in Appendix I in their entirety, with the key words underlined.

Processing

Three types of processing were applied to the speech signals: time compression, wide-dynamic range compression, and time restoration. Time compression and time restoration both change the duration of the speech signal while maintaining its pitch by removing alternate pitch periods. Wide-dynamic range compression was applied to both the time compressed and the normal rate speech. A flow chart in Figure 8 illustrates the sequence of processing applied to each test sentence. (Figure 8)

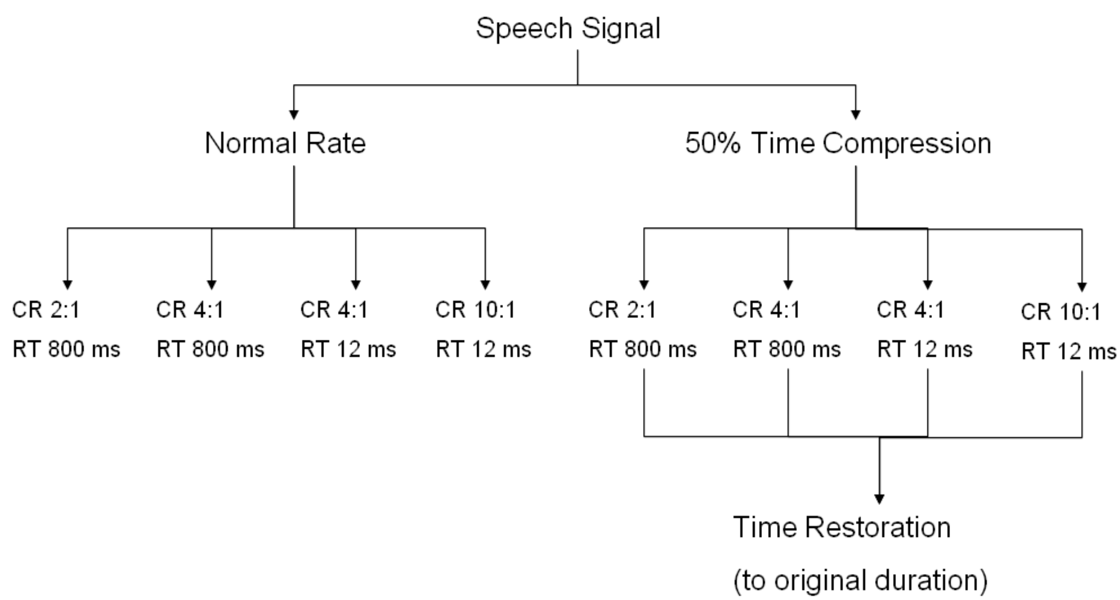

Figure 8. The steps of stimulus processing for each low-probability sentence for all 8 SPIN lists.

Time Compression

Time compression was applied using a computer algorithm (WEDW software, Global Option; http://www.asel.udel.edu/speech/Spch_proc/wedw.htm) to reduce each sentence to 50% of its original length. Fifty percent compression is a fairly typical value chosen when only one time compression condition is tested (Gordon-Salant & Fitzgibbons, 2001, 2004). This value avoids both floor and ceiling effects for older listener with hearing loss. The time compression method used in the WEDW software first tracks the pitch periods of the speech signal, then removes alternate pitch periods. The remaining segments are abutted using a weighted overlap addition method. This sequence of steps preserves the pitch of the speech and does not introduce additional distortion into the signal.

WDRC

Each of the sentences, both the original, normal rate sentences and the time-compressed sentences, were then processed with WDRC amplification. The specific WDRC parameters were variations of compression ratio and release time, chosen so that the interactions of these parameters could be tested across a wide range of distortion values, as measured on the EDI scale. From the previous acoustic measurements made for a wide combination of compression ratios and release times, shown in Figure 3 in the Introduction, a reduced set of compression parameters was chosen for further testing. The reduced set was chosen to result in a range of representative EDI values. The parameters chosen and the corresponding average EDI value for those conditions are given in Table 3. The EDI measurements were made on both the normal rate and time-compressed sentences.

Table 3. The compression parameter manipulations and their corresponding average EDI values for the normal rate and time-compressed speech conditions.

	Mean EDI Value	
Compression Parameters	Normal Rate	Time-Compressed
Compression Ratio: 2:1 Release Time: 800 ms	.10	.10
Compression Ratio: 4:1 Release Time: 800 ms	.16	.16
Compression Ratio: 4:1 Release Time: 12 ms	.25	.25
Compression Ratio: 10:1 Release Time: 12 ms	.34	.34

Statistical analysis was conducted on a random sample of the 1600 processed sentences (200 original sentences x 8 processing conditions). Sixteen sentences were randomly chosen (without replacement) from the data set, two sentences from each of the eight lists. The analysis showed a significant effect of compression parameter [$F(3,45) = 565.06$, $p < .001$], no difference in EDI values between the normal-rate and time-compressed speech [$F(1,15) = .547$, $p = .471$] and no interaction between speech rate and compression parameters on the EDI scale [$F(3,45) = .628$, $p = .601$]. Simple comparisons of the hearing aid conditions showed that each compression condition resulted in higher EDI values than the previous compression condition. This statistical result indicates that the WDRC processing had the same effect on the temporal envelope for both speech rates. This means that if a behavioral interaction is observed, it will be possible to attribute the interaction to the listener, not an acoustic interaction.

All of the stimuli were filtered into two channels, using a 1200 Hz crossover frequency, and then each channel was processed through compression simulation software (Gennum Corporation; GennEM v1.0). The GennEM software is a single-channel compression simulator that operates in the same manner as compression circuits in wearable hearing aids. The adjustable compression parameters were fixed as follows: compression threshold = 40 dB, attack time = 6 ms, which are both commonly-used compression settings. The chosen compression parameters were limited to a single setting each to investigate solely the influence of release time, compression ratio, and the interaction between these two variables. After WDRC processing the channels separately, the two frequency channels were mixed together. The separation and recombination of frequency channels allows for the simulation of a two-channel compression device.

Time Restoration

There is no standard protocol for time restoration methods because it has not been investigated thoroughly. Based on the methods that have been reported in the literature (Wingfield & Tun, 2001; Wingfield et al., 1999), two separate manipulations were applied to the time-compressed speech signal to restore it back to its original length without altering the amount of acoustic information contained in the signal. First, using the WEDW software, pitch periods were added back in to restore the signal to 75% of the original signal length. Second, pauses in the sentence were lengthened by inserting additional silent gaps into the signal at the point where the speaker paused naturally, usually at a phrase boundary. Depending on the length of the sentence and the number of natural pauses present, each sentence had anywhere from one to four silent intervals inserted. The total length of the silent intervals added was 25% of the original sentence length, bringing the length of the time-restored sentence back to the original length.

Temporal waveforms of the three rate conditions for a single example sentence are shown in Figure 9.(Figure 9) In each case the sentence is the same, "You heard Jane called about the van," and is compressed with the same compression parameters: 2:1 compression ratio and 800 ms release time. The waveforms are shown on the same time scale. The top waveform of the figure is the normal rate at the original duration. The middle waveform is the time-compressed condition at half the duration. The bottom waveform is the time-restored condition at the original duration, but with larger pauses between phrases.

Figure 9. Temporal waveforms of the example sentence "You heard Jane called about the van" at the lowest EDI value (.10). The normal rate is shown in the top panel, the time-compressed in the second panel, and time-restored in the bottom panel.

Frequency Response and Overall Level

Stimuli were presented at an individually-chosen overall level in conjunction with constant high-frequency emphasis to ensure audibility for each listener from 500 to 3000 Hz. Audibility is defined as the dB rms level of the sentences above audiometric threshold, with both speech and threshold referenced to dB SPL in a 2 cc coupler. Figure 10 shows the average sensation levels of speech for the eight compression conditions for the young-old and old-old listeners. The zero line on the graph represents threshold, so any values greater than zero are considered audible and any values below zero are considered inaudible. The overall level of speech, as measured in a 2 cc coupler, ranged across listeners from 70 to 85 dB SPL, depending on the listener's degree of hearing loss. For a single listener, the overall level of speech across the 8 listening conditions varied only within a 1 dB range. The time-restored speech conditions are not shown here. Because the time-restoration process involved the insertion of silent gaps into the signal, the measurement of the entire signal (speech and silent gaps) would have been misleading. The time-restoration was performed on the measured and calibrated time-compressed se Time (ms) here. (Figure 10)

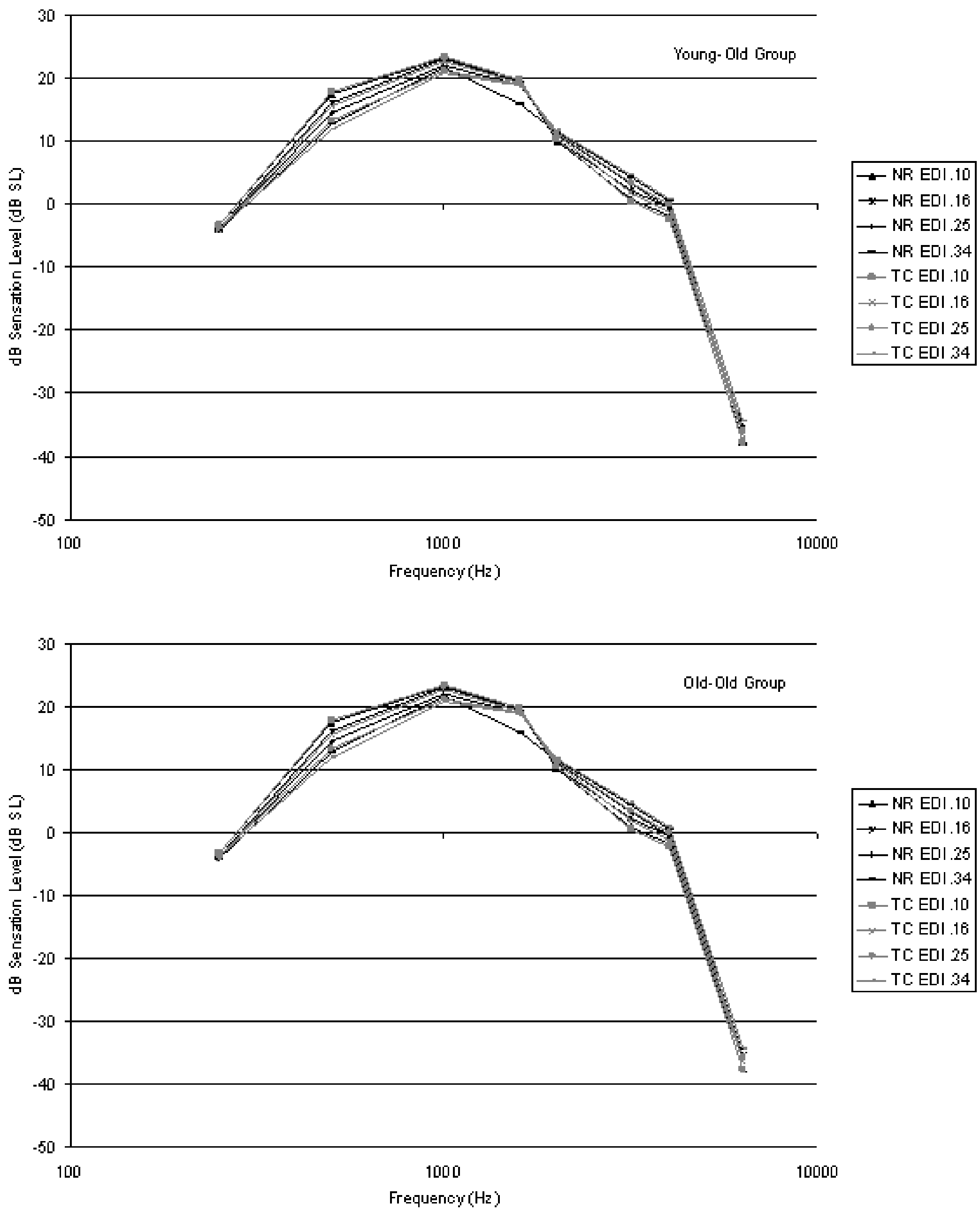

Figure 10. Average speech levels relative to threshold for the young-old and old-old groups. Threshold is represented by the zero line on the graph. The individual lines are the levels for each of the 8 processing conditions. Positive numbers indicate that speech is above threshold and therefore audible. Audibility is achieved from 500 to 3000 Hz.

Procedure

Testing began with a full audiometric and cognitive screening. In general, the better ear of each subject was chosen for subsequent testing. In cases where hearing was symmetrical, the right ear was used.

For speech intelligibility testing, the subject was seated in a double-walled sound-treated booth. The speech stimuli, stored on the hard drive of the test computer, were converted to analog, filtered, and amplified, then presented to the subject via an ER3A insert earphone. A microphone located directly in front of the subject picked up his or her responses and transmitted them to the examiner's headset. A dialog box appeared on a computer monitor in front of the listener to signal the beginning of each trial; however, the subject was not required to make any response via the computer. The intertrial interval was controlled by the examiner and was varied depending upon the amount of time the participant needed to respond.

The test order was randomized in blocks for each participant. Each participant heard all of the normal rate conditions in a block, all of the time-compressed conditions in a block, and all of the time-restored conditions in a block. The order of the blocks was randomized for each subject. Within each of these blocks, the order of WDRC conditions was randomized. The sentence set paired with any particular listening condition was counterbalanced across subjects.

Practice sentences were presented before each of the rate conditions to familiarize the listener with the speech rate of the condition. The practice sentences had minimal WDRC processing applied because the main focus was to familiarize the listener with the talker's voice and with the speech rate. During practice, if the listener had difficulty understanding the signal, the full sentence was typed onto a word processing document shown on the computer monitor, using a large sans serif font (Verdana 26 point font). After the subject had a chance to read the sentence, the sentence was replayed auditorily. This continued until the subject could understand most of the words of several sentences in a row, at which point testing began on the test stimuli. No feedback or repetition was provided during the test phase.

Listeners heard the sentence and repeated it back to the examiner, who transcribed the response orthographically. Sentences were scored on the number of key words correctly repeated. Additions to the sentence were not counted as errors. Contractions also were not counted as errors (e.g., responding "I'll" for "I will").

All testing was completed in one or two sessions for each participant, each session lasting one to three hours, depending on how much testing the participant wished to do in a single day and how much time he or she needed for practice and response during testing.

Results

Statistical Analysis and Hypotheses

The dependent variable was number of words correct transformed to the rationalized arcsine unit (RAU; Studebaker, 1985) scale to stabilize the variance associated with a proportion scale. The within-subject independent variables were speech rate (normal vs. time-compressed), and EDI value (4 values: 0.10, 0.16, 0.25, 0.34). The between-subject independent variable was age (2 groups: young-old and old-old).

The main question to be examined was whether increased EDI values resulted in lower speech recognition scores. Secondary questions were 1) whether old-old adults had lower scores; 2) whether old-old adults were more affected by increasing EDI distortion than young-old adults; 3) whether there was an interaction between EDI value and speech rate; and 4) whether the source of the rapid speech effect was due to reduced processing time or the impoverished acoustic signal created by the time compression processing.

Two of the old-old participants could only complete the normal rate speech condition. Despite extensive training and practice on the time-compressed condition, they could not understand any of the time-compressed speech. Their normal-rate data are not included in these analyses, but they will be discussed separately.

Age x EDI x Speech Rate

The individual speech scores for each listener are shown in figure 11 for the normal rate (top panel) and time-compressed (lower panel) conditions, as a function of age group, EDI value, and speech rate. (Figure 11) The individual scores are indicated by dots and the mean for each subject group per listening condition are indicated by horizontal dashes. From the graph, it can be seen that scores decrease slightly with increasing EDI value, and this decrease is greater for the rapid rate than normal rate speech. As expected, the scores in the rapid rate condition are much lower than the scores in the normal rate condition. There is also higher variability for the rapid rate condition. There does not appear to be an age effect between these two age groups, although there is higher variability in the old-old group than the young-old group.

To examine the effects of the EDI value on speech recognition for the two age groups and the two speech rates, a split-plot ANOVA was conducted, with EDI and Speech Rate as the within-subject repeated measures and Age as the between-subjects variable. It was hypothesized that there would be interaction between EDI and speech rate, such that there would be little or no reduction in speech recognition as EDI increased for the normal rate, and a greater reduction in speech recognition as EDI increased for the rapid rate speech. It was also expected that the old-old group would have lower speech recognition scores than the young-old groups and that they would be more affected by increasing EDI value than the young-old listeners.

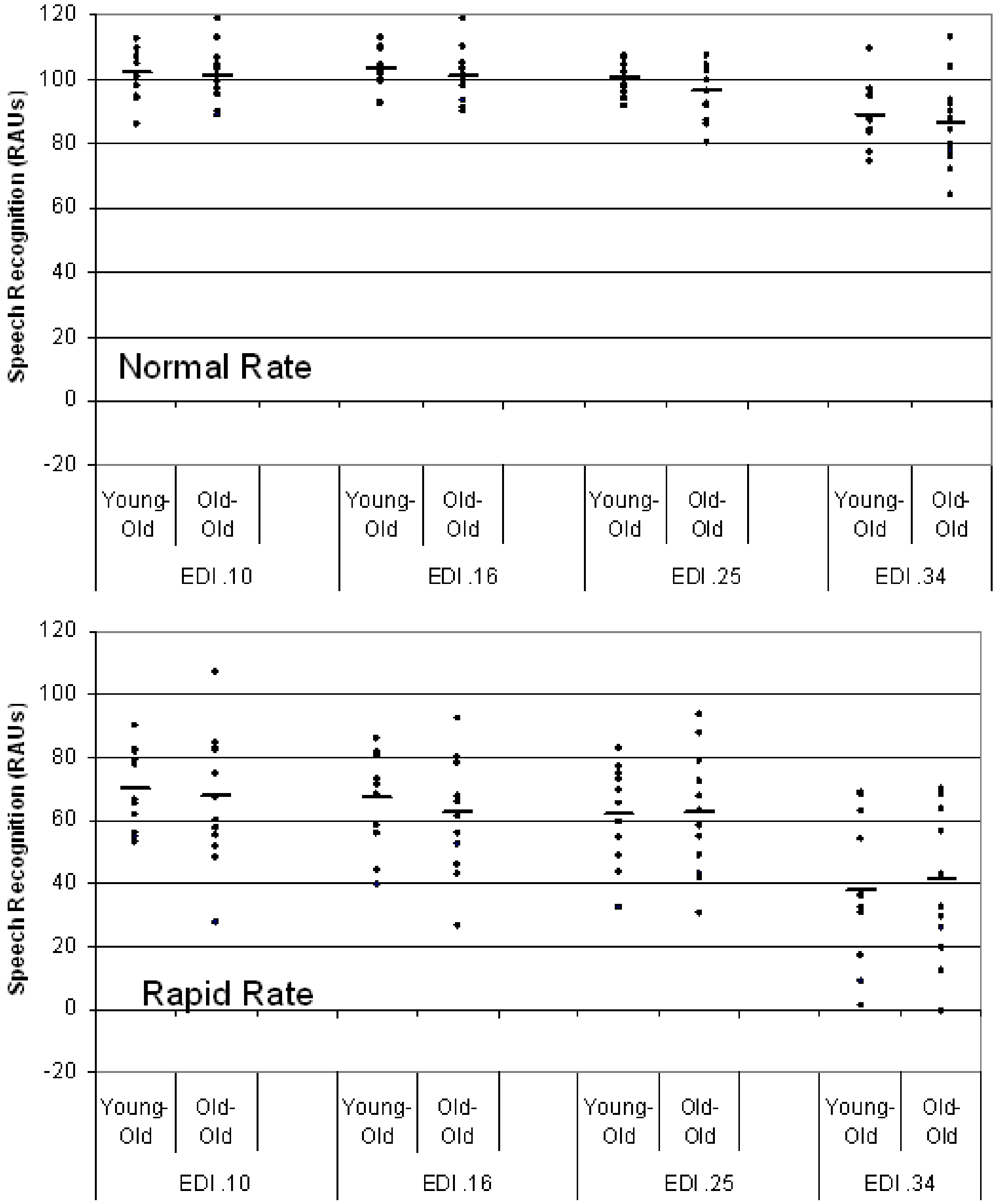

Figure 11. The speech scores (in RAUs) for individual listeners as a function of age group and EDI value. The small dots are the scores for individual listeners and the horizontal dashes are the means for each group at each listening condition.

Age Effects

The analysis showed that there was no overall effect of age group [$F(1,21) = .156$, $p = .697$] and no interaction between age group and either EDI [$F(3,63) = .256$, $p = .857$] or Speech Rate [$F(1,21) = .038$, $p = .847$]. Therefore, the two age groups were collapsed for the remainder of the analysis.

EDI and Speech Rate

From the graph in Figure 12, it can be seen that the effect of increasing EDI is greater for the rapid rate speech than the normal rate speech, as expected. This seems to be particularly true at the highest EDI value. Statistically, there was a significant EDI x Speech Rate interaction [$F(3,63) = 10.4$, $p < .001$]. (Figure 12) To further explore the interaction, simple main effects of EDI at each speech rate were calculated. EDI was significant for both normal rate [$F(3,66) = 27.5$, $p < .001$] and rapid rate speech [$F(3,66) = 42.6$, $p < .001$]. Planned comparisons of individual pairs of EDI values compared speech recognition at each EDI value to speech recognition at the reference EDI value (.10). The lowest EDI value was chosen for the reference as it has the least amount of temporal envelope distortion. Comparing every other amount of temporal distortion to the condition with minimal distortion allows for conclusions about how much temporal envelope distortion is acceptable before it interferes with speech recognition. The results of these contrasts are given in Table 4. To summarize the findings, as EDI increased from .10 to .16, speech recognition did not decrease significantly for either rate condition. As EDI increased to .25, speech recognition decreased for the rapid rate condition, but not the normal rate condition. As EDI increased to the highest level of temporal envelope distortion, speech recognition decreased, relative to the reference condition, for both normal and rapid rate speech.

Table 4. Results of the simple comparisons between EDI values.

	EDI .10 vs EDI .16	EDI .10 vs EDI .25	EDI .10 vs EDI .34
Normal Rate	F = .002	F = 3.552	F = 37.810
	p = .961	p = .073	p < .001*
Rapid Rate	F = 2.394	F = 5.386	F = 64.470
	p = .136	p = .030*	p < .001*

Simple main effects of speech rate at each EDI value would not have provided theoretically important results. The large differences between the two speech rates would have been statistically significant at each EDI value. What was really of interest, then, was not to confirm statistically that there was a significant effect of speech rate at each EDI value, but instead to test whether the magnitude of the speech rate effect was the same across EDI values. This is another way of examining the interaction between EDI and speech rate. A difference score was calculated at each EDI value (the difference in speech recognition between normal and rapid rate). These values are shown indirectly in Figure 12 as the difference between the normal and rapid rate lines. On the graph, the largest difference between speech rates is occurring at the highest EDI value, .34. Given the significant interaction between EDI and rate, the difference score should vary statistically across EDI values. The purpose of this analysis was to determine where the deviations occurred. A one-way ANOVA revealed that the magnitude of the speech rate effect depended upon the EDI level [$F(3,66) = 10.211$, $p < .001$]. Each speech rate effect score was compared to the speech rate effect score at the lowest EDI value (.10). The only comparison that was significantly different from the effect at EDI .10 was the speech rate effect at the highest EDI value, .34. This can be interpreted to mean that the two rate functions were parallel for the lowest three EDI values (.10, .16, and .25), but diverged from parallel at the highest EDI value.

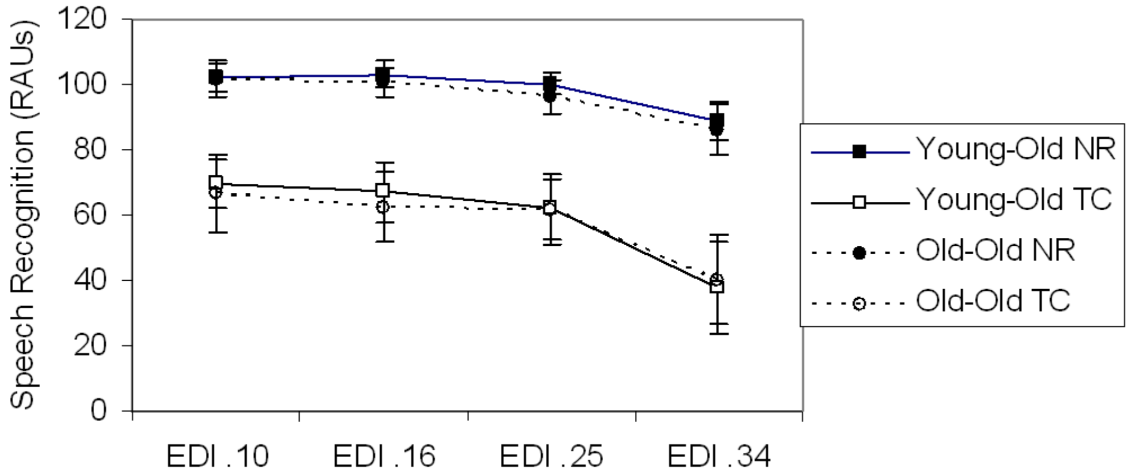

Figure 12. Speech recognition score (in RAUs) for the young-old and old-old listeners for the normal rate (NR) and time-compressed (TC) conditions as a function of EDI level.

Source of Rapid Speech Effect

The source of the rapid speech rate effect for older listeners is not known with certainty. The two likely possibilities for the lowered speech recognition scores are reduced processing time or reduced acoustic redundancy. The time restoration condition was included to help separate these two possibilities by restoring the speech signal to its original length (thereby restoring processing time) without restoring the lost acoustic redundancy. If the rapid speech effect were due only to reduced processing time, then scores in the time restored condition would be restored back to the scores in the normal rate condition. Conversely, if the rapid speech effect were due only to reduced acoustic redundancy, then scores in the time restored condition would not differ from scores in the time-compressed condition. If both reduced processing time and reduced redundancy contributed to the rapid speech effect, the scores in the time-restored condition would be better than the time compressed condition, but worse than the normal rate condition.

The three speech rate conditions are shown together in Figure 13. (Figure 13)The set-up of the graph is the same as previous figures of results, with the time-restored data added as another series. A three-way split-plot ANOVA (EDI x Speech Rate) was conducted, now with three levels of speech rate and age as the between-groups variable. There was no significant age effect, nor any interactions between age and the other variables. The ANOVA revealed a significant EDI by Speech Rate interaction [$F(6,132) = 734.807$, $p < .001$]. To further explore this analysis, a series of post-hoc *t*-tests were conducted, with the alpha level corrected for multiple comparisons using the Bonferroni correction. Because the Bonferroni correction is very stringent, family-wise error was set to $\alpha = .10$. With this correction, the criterion for a significant difference was $p < .0125$. For this particular analysis, neither the differences between EDI values at each speech rate nor the difference between normal rate and time compressed speech were of interest. Therefore, the only comparisons conducted were time-compressed versus time-restored at each EDI value and normal-rate versus time-restored at each EDI value. This meant that eight comparisons were made.

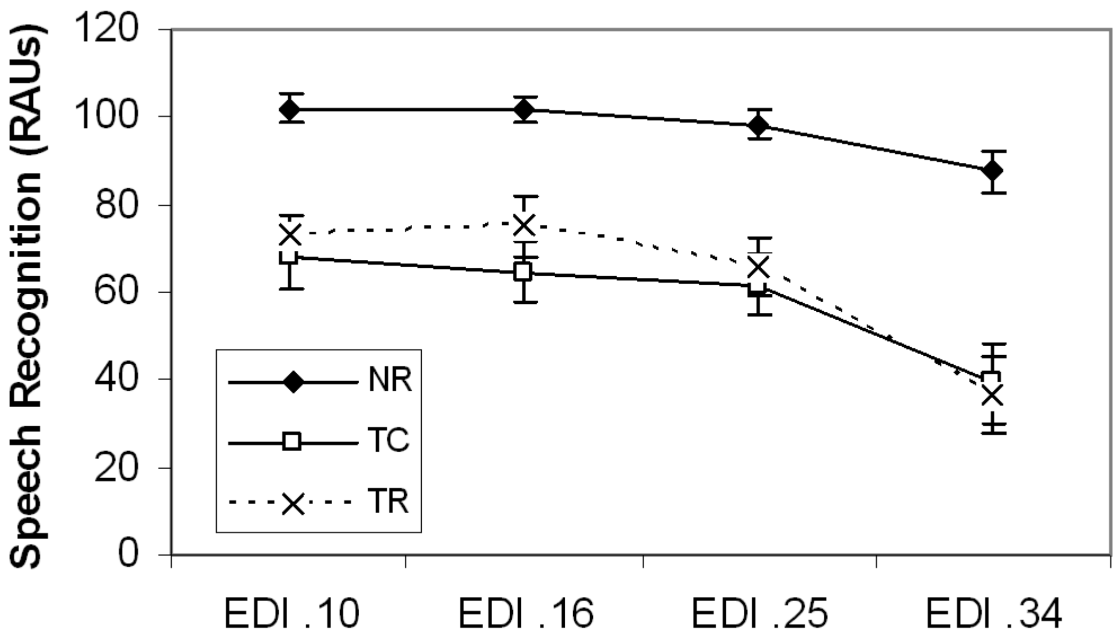

Figure 13. Speech recognition scores (in RAUs) collapsed across age groups for the normal rate (NR), time-compressed (TC) and time-restored (TR) conditions.

The normal rate and time-restored conditions were significantly different at each EDI value ($p < .0125$). There were no significant differences between the time-compressed and time-restored conditions except at one EDI value (EDI .16: $t(22) = 3.538$, $p =$ .002). This pattern of results suggests that the scores in the time-restored condition are similar to the time-compressed scores, but not the normal-rate scores.

Characteristics of the Two Subjects with Incomplete Data

The two old-old subjects who could not complete the time-compressed conditions are identified in Table 1 and 2 as participants 203 and 211. These participants were not clearly distinguishable from the other participants by low scores on the memory screening tasks, nor did they have the worst thresholds. Although both of these subjects were in the old-old group, they were not the two oldest subjects of the sample. The normal-rate speech recognition scores for these two listeners are plotted in Figure 14, along with the average scores of the other participants in both rate conditions. It can be seen that these two participants had much lower scores on the normal-rate condition than the group of participants who were able to complete the entire protocol. In fact, the normal-rate scores of these two participants were similar to the time-compressed recognition scores of the group of participants. (Figure 14)

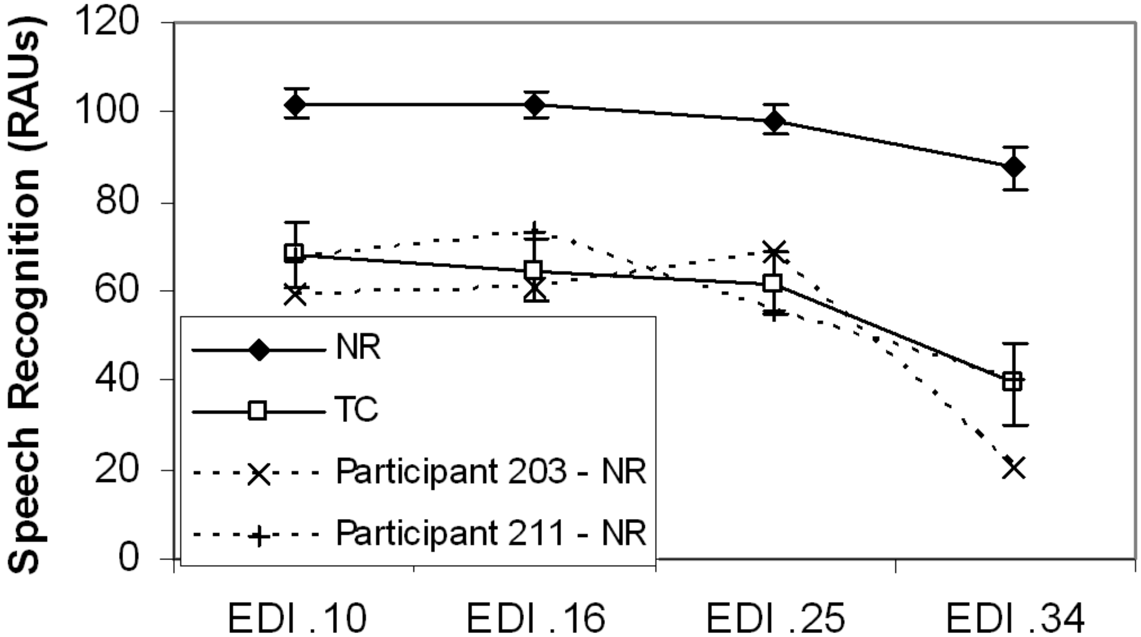

Figure 14. The normal-rate speech recognition scores for the two participants (203 and 211) who could not complete the time-compressed condition. For reference, the mean scores for all other participants are shown for both the normal rate and time-compressed conditions. It can be seen that the scores of the outliers on the normal-rate speech are more similar to the other participants' scores for time-compressed speech than normal-rate speech.

Discussion

The main finding of this study is that both young-old and old-old listeners are equally susceptible to moderate to severe changes of the temporal envelope, particularly when acoustic redundancy is reduced in the speech signal.

Age Effect

Contrary to expectations based on the literature, there was no overall effect of age between the young-old and old-old listener groups. The results of the current study showed that both the young-old and old-old group were susceptible to distortion and to the combined distortions of temporal envelope changes and time-compressed speech. However, it is not known whether the young-old and old-old listeners participating in this study would have similar results as listeners under the age of 60. Previous research would indicate that there should have been an interaction between age group and listening condition. Specifically, much previous research has shown that old-old listeners are much more susceptible to the effects of acoustic distortion and particularly multiple acoustic distortions than young-old listeners (Humes & Christopherson, 1991; Magnusson, 1996; Nabelek, 1988). The distortions tested in the current study, namely WDRC and time-compression, have not been tested for their impact on young-old versus old-old listeners. The other studies cited here that showed an age effect within this same age range tested different types of temporal distortions; namely, reverberation, filtering, and speech in noise. It is possible that age-related susceptibility to distortions differs for different types of manipulations. It will be the focus of further research to understand how these types of distortions differ from one another and why they have varied effects for older listeners.

Having said that there was no overall group age effect for those listeners who completed the entire protocol, it is important to consider the two older listeners with incomplete data. It is not irrelevant that out of the 14 listeners in the old-old group, two of them had very low speech recognition scores compared to the rest of the listeners even for the normal-rate speech and could not complete the time-compressed condition at all.

If only the normal-rate condition had been tested, these two listeners would have been included in the analysis and it would have appeared that there was a modest difference in speech recognition between the two age groups (although this potential effect was not tested statistically). Increasing variability in speech recognition with increasing age is a common finding (CHABA, 1988; Helfer & Huntley, 1991; Humes, 1996, 2002; Humes & Christopherson, 1991; Humes & Roberts, 1990; Humes et al., 1994), which was also found in the current study. This variability can be seen in the individual scores of the of old-old subjects in Figure 11, even with the two outlying subjects removed. Much work has been done to determine whether the individual variability is due to deficits at the peripheral, central auditory, or cognitive level, but this is an issue the current study cannot resolve.

Temporal Envelope Changes and Rate Effects

The lowered scores for the time-compressed condition were consistent with expectations from the literature. In the current study, scores decreased by an average of 37% when speech rate was decreased from normal to 50% time compression. At 50% uniform time compression for low-context sentence materials, such as was used here, other studies have also shown the decrease in speech recognition for older listeners to be about 35-40% change (Gordon-Salant & Fitzgibbons, 2001, 2004; Tun, 1998; Versfeld & Dreschler, 2002). The similarity of the rate effect to much of the previous research suggests a successful implementation of the time-compression processing.

The more interesting aspect of the rapid speech effect, however, was in the interaction with temporal envelope distortion. We can be fairly certain that the interaction tells us about the listener, rather than simply an acoustic interaction. Recall that, as measured on the EDI scale, there was no acoustic interaction between speech rate and EDI. That is, the measured EDI value was the same for normal rate and time-compressed speech for the same compression parameters. Therefore, the behavioral interaction observed is not an artifact of the stimulus processing. The statistical source of the interaction was at the highest level of envelope distortion, at which point the difference between the normal rate and time-compressed condition was greater than it had been for the lower levels of envelope distortion. There was a rate effect for small to medium temporal envelope distortions, but the rate effect was even greater at large temporal envelope distortions. This finding is consistent with other research on multiple distortions (Gordon-Salant & Fitzgibbons, 1993, 1995, 1995, 2004; Tun, 1998), particularly those in which one of the distortions was time-compression.

The consistency across the literature of this interaction effect with time-compression suggests that listeners are making use of alternative resources or cues in the normal-rate condition to compensate for the introduction of the second distortion. When the distortion is combined with time-compression, it becomes more difficult to use the redundant mechanism, as seen for large temporal envelope distortions.

What is the nature of the redundant mechanism? For time-compressed speech, two major hypotheses are considered: loss of additional processing time, or loss of acoustic redundancy. In the process of creating time-compressed speech, the total length of the utterance is decreased, which might be consistent with the effect being due to loss of processing time. To choose between these two possibilities, listeners were also tested with time-restored speech, in which the speech was returned to its original duration without replacing any of the removed acoustic information. Results were consistent with the acoustic redundancy hypothesis for the most part. Recognition for the time-restored speech did not differ from the time-compressed speech, but differed significantly from the normal rate speech. This result indicates that reduced scores in the time-compressed condition were not due to loss of necessary processing time but were due to the loss of acoustic redundancy.[4] A recent investigation of the source of the rapid speech effect in older listeners is consistent with the acoustic redundancy hypothesis

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[4] Note, however, that at one of the lower levels of temporal envelope distortion, there may have been a small role of processing time, suggesting that under some listening conditions acoustic redundancy may not account for all of the variance. It is beyond the scope of the current study to define the properties of those listening conditions in which processing time also has a role.

To interpret the interaction between temporal envelope alteration and speech rate in the current study, then, the listeners were using temporal envelope information. For normal-rate speech, alterations to the temporal envelope were not as detrimental to speech recognition because the listener could access additional, redundant cues in the acoustic signal. In the time-compressed condition, the acoustic signal was made less redundant, making the impact of temporal envelope alteration even greater. Previous studies have shown that older listeners rely on integrating acoustic cues for recognition more than younger listeners (Ohde & Abou-Khalil, 2001) and that they have lower recognition performance when one dimension of the speech signal is restricted (Souza, 2000; Souza & Kitch, 2001). Therefore, as in the current study, older listeners seem to rely on redundancy in the signal and removing this is detrimental to their speech recognition.

Note that the two outlying old-old subjects were recognizing speech in the normal rate condition like most of the listeners were recognizing speech in the rapid condition. It is possible that these two listeners were already listening to a degraded acoustic signal even prior to time-compression. This would be consistent with the hypothesis that some older listeners have reduced speech recognition due to a lower functional signal-to-noise ratio (Gordon-Salant & Fitzgibbons, 1995). This hypothesis is not very specific, in that the deficit may be occurring anywhere from the peripheral to the cognitive level. That is, internal noise could be added at any point along the system, or the signal itself could be degraded at any point. However, this hypothesis is functionally different from the cognitive theories of reduced processing time or divided resources. It does not contradict the reduced inhibition hypothesis, though, since reduced definition of irrelevant items may be thought of as increased noise in the system. From the results of the current study, it is possible that rapid speech simulates the difficulties experienced by some older listeners. This may provide a route to understand the individual variability in older listeners. Before this can happen, further study is needed to determine whether rapid speech is simulating the mechanism damaged in some older adults. A first step in this process would be to do an error analysis comparing the types of errors made by the two outliers in the normal rate condition and the remaining listeners for the rapid rate condition. Similar error patterns would suggest that the rapid speech condition did simulate the listening experience of the two low-performing listeners.

The EDI Scale as a Measure of Temporal Envelope Importance

The EDI scale may be a tool to quantify the importance of the temporal envelope in speech recognition. The results of this study showed that the amount of change to the temporal envelope, as quantified with the EDI measurement, did affect speech recognition for this group of hearing-impaired listeners. Recall that low EDI values represent little alteration of the temporal envelope and high EDI values represent greater alteration of the temporal envelope. In this study, listeners were unaffected by small changes to the envelope; that is, increasing the alteration from a value of .10 to .16 had no significant effect on speech recognition. It appears that listeners are tolerant to some temporal envelope changes, even when acoustic redundancy is reduced, as in the time-compressed speech condition. Increasing the alteration even further, to .25 and then to .34, had a significant detrimental effect on recognition, showing that the listeners were affected by alterations to the temporal envelope.

Is this finding applicable only to the low-context sentence materials used in this study? Previous research using the EDI measurement tool with nonsense syllables reveals a similar threshold of tolerable envelope alteration (Jenstad & Souza, 2005). In that study, we found that EDI levels of about .20 and above were associated with decreased recognition compared to an unaltered speech signal. However, this cut-off limit may not be applicable to high-context speech materials in which recognition is more resistant to temporal envelope changes.

The results of both the current study and the previous research with nonsense syllables are encouraging in showing that the EDI measurement may provide a good method to define maximum tolerable envelope alteration. Several questions still need to be answered through research before the EDI can be a useful tool. Further validation of the EDI scale would need to address several areas.

First, how does the maximum tolerable value vary across speech types and listening conditions? So far, it seems similar for low-context sentences and nonsense syllables in quiet, for both normal rate and rapid speech. As addressed above, high-context sentences would likely have a different maximum. How does the EDI scale interact with other distortion conditions? Previous acoustic research showed that slightly modulated background noise had the effect of almost eliminating WDRC acoustic alterations. It would seem, then, that it would take very large degrees of compression to reach the .20 point on the EDI scale for speech in background noise. It is possible, though, that the maximum tolerable EDI value in noise occurs at a much lower level. This is also true of other distortions, such as reverberation, casual speech, or some of the other possible acoustic manipulations. We also only ensured audibility from 500 to 3000 Hz, as a fairly typical simulation of hearing aid fittings for listeners with sloping high-frequency hearing loss. Addition of more high frequencies to the listening situation may have changed the results of the EDI measurement; with a broader frequency range, the listeners might be more resistant to temporal envelope changes than they were in this narrower listening range.

Second, how does the maximum EDI value vary across listeners? In the current study and in the previous nonsense syllable study, all listeners had hearing losses within the mild to moderately-severe range. It is known that listeners with severe to profound hearing loss rely more on the temporal envelope of speech for recognition (Boothroyd et al., 1988; Rosen, Faulkner, & Smith, 1990), and would likely tolerate less alteration of the envelope.

Third, what measurement parameters of the EDI are most predictive of speech recognition? In the current study, the entire speech signal was treated as a single band for the EDI measurement. However, it may be that the temporal envelope is more important in some frequency bands than others (Steeneken & Houtgast, 1999; Steeneken &

Houtgast, 2002), or that quantification of the temporal envelope in individual frequency bands would provide a more precise estimate. Filtering the signal into separate frequency bands before applying the EDI measurement would provide a way to look at this aspect. It would be particularly helpful to incorporate some of the methods used the STI measurement, which does use separate frequency bands, albeit for nonspeech and noncompressed signals. Also, it is known that temporal cues are more important for some speech sounds (such as stops) than others (such as vowels), and for some segments of the speech signal (such as transitions) than others (such as steady-state portions of a speech sound) (Faulkner & Rosen, 1999; Ohde & Stevens, 1983; Repp, 1979; Rosen et al., 1994; Shinn & Blumstein, 1984). In the current study, the EDI was applied to entire sentences, including the segments for which temporal cues were important and those for which spectral cues were most important. To validate the EDI and its usefulness in quantifying relevant temporal envelope changes, it will be important to examine local changes in EDI at transition points and relate those values back to recognition of individual speech elements.

Fourth, does the EDI apply to envelope-expanded speech? The EDI measured here and in the nonsense-syllable study was only for compressed speech. Theoretically, though, since the EDI is based on the absolute value of the differences between two envelopes, the same measurement could be applied to expanded speech. Would similar increases in expansion be detrimental to speech recognition? It is possible that the scales would have to be considered differently, since some types of temporal expansion have been known to enhance speech recognition (Apoux, Tribut, Debruille, & Lorenzi, 2004; Krause & Braida, 2004)

Fifth, is the EDI only quantifying temporal changes and their effect on speech recognition? An additional way to validate the EDI scale is to apply it to speech from which most of the spectral information has been removed, such as the signal-correlated noise (SCN; Souza, 2000; Souza & Kitch, 2001; Souza & Turner, 1996, 1998). This speech signal has been used to understand the amount of information carried by the temporal envelope alone. Using the EDI scale in conjunction with speech recognition for SCN speech would allow us to ensure that we are quantifying the temporal changes and their effect upon recognition.

Sixth, is the EDI independent of compression parameters? This study was designed to examine the effects of compression on speech recognition, but to do so in a parameter-independent way. As noted in the introduction, compression parameters can interact with one another in the acoustic effects they have. For instance, at a low compression ratio, release time has very little acoustic effect even for widely different nominal values. At high compression ratios, changing release time has a large acoustic effect. It is difficult, therefore, to do research on the behavioral effects of these parameters without a good quantification of their acoustic effects. The EDI was intended to provide a method to quantify the effects of compression. From a large set of acoustic measures in which compression ratio and release time were varied for a two-channel compression system, I chose four combinations of compression ratio and release time that provided distinctly different EDI values that were relatively equally-spaced on the scale. The two lowest EDI values in this study were derived using compression combinations of a 2:1 compression ratio paired with an 800 ms release time and a 4:1 compression ratio paired with an 800 ms release time, both slow-acting compression conditions. In terms of speech recognition, these conditions did not differ from one another. The next highest EDI value was created with a combination of a 4:1 compression ratio and a 12 ms release time, a fast-acting compression condition. This condition was significantly different from the condition with the lowest EDI value. If the EDI scale is truly parameter-independent, then any other compression combinations that result in values between .10 and .16 should not differ from one another. Equivalent EDI values derived with any combination of compression parameters should result in equivalent recognition scores and, importantly, in similar error patterns. This will be the focus of future investigation. Evidence that the scale is parameter-independent is already accumulating: the similar results for the nonsense syllable recognition study were obtained with a 3:1 compression ratio and single-channel compression.

Implications for Compression Amplification

These results show that there are significant differences among compression types, depending upon the amount of acoustic distortion introduced by the compression parameters. This result was found when context was controlled, forcing the listener to rely on the acoustic signal rather than compensating with other mechanisms. We also ensured that the conditions tested were acoustically different, which is not usually done in other studies. If we had chosen to compare only release time while holding compression ratio constant at 2:1, the conditions would have been very similar acoustically. Choosing the conditions on the basis of nominal parameter settings rather than actual acoustic differences would have meant searching for a very small behavioral effect indeed. In addition, the results would have been less globally-applicable. Once further validation of the EDI scale is conducted it will be a mechanism by which WDRC processing can be evaluated, regardless of the parameter types implemented. If it becomes evident that EDI values within or above the range .20 to .25 consistently result in reduced recognition, then acoustic measures will be sufficient to determine whether a certain set of compression parameters is acceptable or not.

Conclusions

In conclusion, the following inferences can be made from the results of this study:

1) Older listeners with hearing loss were susceptible to moderate changes in the temporal envelope of speech even for normal rate speech. When this information was altered sufficiently, recognition decreased.

2) Older listeners with hearing loss were equally susceptible to moderate changes in the temporal envelope for rapid rate speech as normal rate speech.

3) Older listeners were more susceptible to severe temporal envelope distortions at the higher speech rate than the normal speech rate.

4) Older listeners were likely using redundancy in the signal to decipher speech with distorted temporal envelope information when it was presented at a normal rate. Removing redundancy while maintaining sentence duration reduced recognition performance.

5) a) There was not a statistically-significant decrease in speech recognition with increasing age. Comparisons of listeners below age 75 and those aged 75 years and over, matched as a group for hearing losses, showed that they did not differ in their speech recognition for this low-context speech, either in conditions of reduced redundancy or in conditions of increasing temporal envelope alteration.

b) However, some *individual* listeners over age 75 had difficulties with speech recognition; two of the fourteen old-old listeners had very reduced speech recognition compared to the rest of the group. The mechanism responsible for this reduction is unknown. Further analysis of the error patterns made by the remaining listeners on rapid speech will be conducted to see if the rapid speech condition simulates the errors made by the two outlying listeners.

References

Apoux, F., Crouzet, O., & Lorenzi, C. (2001). Temporal envelope expansion of speech in noise for normal-hearing and hearing-impaired listeners: effects on identification performance and response times. *Hear Res, 153*(1-2), 123-131.

Apoux, F., Tribut, N., Debruille, X., & Lorenzi, C. (2004). Identification of envelope-expanded sentences in normal-hearing and hearing-impaired listeners. *Hear Res, 189*(1-2), 13-24.

Arons, B. (1992). *Techniques, Perception, and Applications of Time-Compressed Speech.* Paper presented at the American Voice I/O Society.

Auer, T. (2003). Stimulus-based similarity and the recognition of spoken words. *J Acoust Soc Am, 114*(4), 2421.

Bashore, T. R., vanderMolen, M. W., Ridderinkhof, K. R., & Wylie, S. A. (1997). Is the age-complexity effect mediated by reductions in a general processing resource? *Biological Psychology, 45*(1-3), 263-282.

Beaman, C. P. (2005). Irrelevant sound effects amongst younger and older adults: Objective findings and subjective insights. *European Journal of Cognitive Psychology, 17*(2), 241-265.

Bentler, R. A., & Nelson, J. A. (1997). Assessing release-time options in a two-channel ACC hearing aid. *Am J Audiol, 6*(1), 43-51.

Bilger, R. C., Nuetzel, J. M., Rabinowitz, W. M., & Rzeczkowski, C. (1984). Standardization of a test of speech perception in noise. *J Speech Hear Res, 27*(1), 32-48.

Boike, K. T. (2004). *Influence of Age on the Recognition of Amplitude Compressed Speech in Backgrounds Varying in Temporal Complexity.* Unpublished Dissertation, University of Washington, Seattle.

Boike, K. T., & Souza, P. E. (2000). Effect of compression ratio on speech recognition and speech-quality ratings with wide dynamic range compression amplification. *J Speech Hear Res, 43*, 456-468.

Boothroyd, A. (1993). Speech perception, sensorineural hearing loss, and hearing aids. In G. A. Studebaker & I. Hockberg (Eds.), *Acoustical Factors Affecting Hearing Aid Performance* (2nd ed., pp. 277-300). Boston: Allyn and Bacon.

Boothroyd, A., Springer, N., Smith, L., & Schulman, J. (1988). Amplitude compression and profound hearing loss. *J Speech Hear Res, 31*(3), 362-376.

CHABA. (1988). Speech understanding and aging. Working Group on Speech Understanding and Aging. Committee on Hearing, Bioacoustics, and Biomechanics, Commission on Behavioral and Social Sciences and Education, National Research Council. *J Acoust Soc Am, 83*(3), 859-895.

Cheesman, M. F., Hepburn, D., Armitage, J. C., & Marshall, K. (1995). Comparison of growth of masking functions and speech discrimination abilities in younger and older adults. *Audiology, 34*(6), 321-333.

Cohen, G., & Faulkner, D. (1983). Word recognition: age differences in contextual facilitation effects. *Br J Psychol, 74 (Pt 2)*, 239-251.

Coughlin, M., Kewley-Port, D., & Humes, L. E. (1998). The relation between identification and discrimination of vowels in young and elderly listeners. *J Acoust Soc Am, 104*(6), 3597-3607.

Crain, T. R., & Yund, E. W. (1995). The effect of multichannel compression on vowel and stop-consonant discrimination in normal-hearing and hearing-impaired subjects. *Ear Hear, 16*(5), 529-543.

Crouzet, O., & Ainsworth, W. A. (2001). Envelope information in speech processing: Acoustic-phonetic analysis vs. auditory figure-ground segregation. *Proceedings of Eurospeech 2001, 7th European Conference on Speech Communication and Technology*.

Crouzet, O., & Ainsworth, W. A. (2001). On the various influences of envelope information on the perception of speech in adverse conditions: An analysis of between-channel envelope correlation, *Workshop on Consistent and Reliable Acoustic Cues for Sound Analysis*.Aalborg, Denmark.

Dallos, P. (1997). Outer hair cells: the inside story. *Ann Otol Rhinol Laryngol Suppl, 168*, 16-22.

De Gennaro, S., Braida, L. D., & Durlach, N. I. (1986). Multichannel syllabic compression for severely impaired listeners. *J Rehabil Res Dev, 23*(1), 17-24.

Dillon, H. (1996). Compression? Yes, but for low or high frequencies, for low or high intensities, and with what response times? *Ear Hear, 17*(4), 287-307.

Dirks, D. D., Takayanagi, S., Moshfegh, A., Noffsinger, P. D., & Fausti, S. A. (2001). Examination of the neighborhood activation theory in normal and hearing-impaired listeners. *Ear Hear, 22*(1), 1-13.

Divenyi, P. L., & Haupt, K. M. (1997). Audiological correlates of speech understanding deficits in elderly listeners with mild-to-moderate hearing loss. I. Age and lateral asymmetry effects. *Ear Hear, 18*(1), 42-61.

Divenyi, P. L., & Haupt, K. M. (1997). Audiological correlates of speech understanding deficits in elderly listeners with mild-to-moderate hearing loss. II. Correlation analysis. *Ear Hear, 18*(2), 100-113.

Divenyi, P. L., & Haupt, K. M. (1997). Audiological correlates of speech understanding deficits in elderly listeners with mild-to-moderate hearing loss. III. Factor representation. *Ear Hear, 18*(3), 189-201.

Dorman, M. F., Marton, K., Hannley, M. T., & Lindholm, J. M. (1985). Phonetic identification by elderly normal and hearing-impaired listeners. *J Acoust Soc Am, 77*(2), 664-670.

Dreschler, W. A. (1989). Phoneme perception via hearing aids with and without compression and the role of temporal resolution. *Audiology, 28*(1), 49-60.

Dreschler, W. A. (1993). Compression in hearing aids: Frequency dependence and effect in background noise. In J. Beilin & G. Jensen (Eds.), *Recent Developments in Hearing Instrument Technology* (Vol. 15th Danavox Symposium, pp. 253-272). Scanticon, Kolding, DK: Danavox.

Drullman, R. (1995). Speech intelligibility in noise: relative contribution of speech elements above and below the noise level. *J Acoust Soc Am, 98*(3), 1796-1798.

Dubno, J. R., Ahlstrom, J. B., & Horwitz, A. R. (2000). Use of context by young and aged adults with normal hearing. *J Acoust Soc Am, 107*(1), 538-546.

Dubno, J. R., Horwitz, A. R., & Ahlstrom, J. B. (2002). Benefit of modulated maskers for speech recognition by younger and older adults with normal hearing. *J Acoust Soc Am, 111*(6), 2897-2907.

Dubno, J. R., Lee, F. S., Matthews, L. J., & Mills, J. H. (1997). Age-related and gender-related changes in monaural speech recognition. *J Speech Lang Hear Res, 40*(2), 444-452.

Edwards, B. W. (2004). Hearing aids and hearing impairment. In J. E. Greenberg & W. A. Ainsworth & A. N. Popper & R. R. Fay (Eds.), *Speech Processing in the Auditory System* (Vol. 18, pp. 339-421). New York: Springer.

Faulkner, A., Ball, V., Rosen, S., Moore, B. C., & Fourcin, A. (1992). Speech pattern hearing aids for the profoundly hearing impaired: speech perception and auditory abilities. *J Acoust Soc Am, 91*(4 Pt 1), 2136-2155.

Faulkner, A., & Rosen, S. (1999). Contributions of temporal encodings of voicing, voicelessness, fundamental frequency, and amplitude variation to audio-visual and auditory speech perception. *J Acoust Soc Am, 106*(4 Pt 1), 2063-2073.

Festen, J. M., van Dijkhuizen, J. N., & Plomp, R. (1990). Considerations on adaptive gain and frequency response in hearing aids. *Acta Otolaryngol Suppl, 469*, 196-201.

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res, 12*(3), 189-198.

Fortune, T. W., Woodruff, B. D., & Preves, D. A. (1994). A new technique for quantifying temporal envelope contrasts. *Ear Hear, 15*(1), 93-99.

Fox, R. A., Wall, L. G., & Gokcen, J. (1992). Age-related differences in processing dynamic information to identify vowel quality. *J Speech Hear Res, 35*(4), 892-902.

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

Frisina, R. D. (2001). Possible neurochemical and neuroanatomical bases of age-related hearing loss - Presbycusis. *Seminars in Hearing, 22*(3), 213-225.

Fullgrabe, C., Meyer, B., & Lorenzi, C. (2003). Effect of cochlear damage on the detection of complex temporal envelopes. *Hear Res, 178*(1-2), 35-43.

Gatehouse, S., & Gordon, J. (1990). Response times to speech stimuli as measures of benefit from amplification. *Br J Audiol, 24*(1), 63-68.

Gatehouse, S., Naylor, G., & Elberling, C. (2003). Benefits from hearing aids in relation to the interaction between the user and the environment. *Int J Audiol, 42 Suppl 1*, S77-85.

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

Gelfand, S. A., Piper, N., & Silman, S. (1986). Consonant recognition in quiet and in noise with aging among normal hearing listeners. *J Acoust Soc Am, 80*(6), 1589-1598.

Gordon-Salant, S. (1986). Recognition of natural and time/intensity altered CVs by young and elderly subjects with normal hearing. *J Acoust Soc Am, 80*(6), 1599-1607.

Gordon-Salant, S. (1987). Age-related differences in speech recognition performance as a function of test format and paradigm. *Ear Hear, 8*(5), 277-282.

Gordon-Salant, S. (1987). Consonant recognition and confusion patterns among elderly hearing-impaired subjects. *Ear Hear, 8*(5), 270-276.

Gordon-Salant, S., & Fitzgibbons, P. J. (1993). Temporal factors and speech recognition performance in young and elderly listeners. *J Speech Hear Res, 36*(6), 1276-1285.

Gordon-Salant, S., & Fitzgibbons, P. J. (1995). Comparing recognition of distorted speech using an equivalent signal-to-noise ratio index. *J Speech Hear Res, 38*(3), 706-713.

Gordon-Salant, S., & Fitzgibbons, P. J. (1995). Recognition of multiply degraded speech by young and elderly listeners. *J Speech Hear Res, 38*(5), 1150-1156.

Gordon-Salant, S., & Fitzgibbons, P. J. (1997). Selected cognitive factors and speech recognition performance among young and elderly listeners. *J Speech Lang Hear Res, 40*(2), 423-431.

Gordon-Salant, S., & Fitzgibbons, P. J. (2001). Sources of age-related recognition difficulty for time-compressed speech. *Journal of Speech Language and Hearing Research, 44*(4), 709-719.

Gordon-Salant, S., & Fitzgibbons, P. J. (2004). Effects of stimulus and noise rate variability on speech perception by younger and older adults. *J Acoust Soc Am, 115*(4), 1808-1817.

Hasher, L., Tonev, S. T., Lustig, C., & Zacks, R. (2001). Inhibitory Control, Environment Support, and Self-Initiated Processing in Aging. In M. Naveh-Benjamin & M. Moscovitch & H. L. Roediger (Eds.), *Perspectives on Human Memory and*

Cognitive Aging: Essays in Honour of Fergus Craik (pp. 286-297). New York: Psychology Press.

Hedrick, M. (1997). Effect of acoustic cues on labeling fricatives and affricates. *J Speech Lang Hear Res, 40*(4), 925-938.

Hedrick, M. S., & Carney, A. E. (1997). Effect of relative amplitude and formant transitions on perception of place of articulation by adult listeners with cochlear implants. *J Speech Lang Hear Res, 40*(6), 1445-1457.

Hedrick, M. S., & Jesteadt, W. (1996). Effect of relative amplitude, presentation level, and vowel duration on perception of voiceless stop consonants by normal and hearing-impaired listeners. *J Acoust Soc Am, 100*(5), 3398-3407.

Hedrick, M. S., Schulte, L., & Jesteadt, W. (1995). Effect of relative and overall amplitude on perception of voiceless stop consonants by listeners with normal and impaired hearing. *J Acoust Soc Am, 98*(3), 1292-1303.

Hedrick, M. S., & Younger, M. S. (2001). Perceptual weighting of relative amplitude and formant transition cues in aided CV syllables. *J Speech Hear Res, 44*, 964-974.

Helfer, K. S., & Huntley, R. A. (1991). Aging and consonant errors in reverberation and noise. *J Acoust Soc Am, 90*(4 Pt 1), 1786-1796.

Hohmann, V., & Kollmeier, B. (1995). The effect of multichannel dynamic compression on speech intelligibility. *J Acoust Soc Am, 97*(2), 1191-1195.

Hudspeth, A. (1997). Mechanical amplification of stimuli by hair cells. *Curr Opin Neurobiol, 7*(4), 480-486.

Humes, L. E. (1993). Some temporal factors affecting speech recognition. In G. A. Studebaker & I. Hockberg (Eds.), *Acoustical Factors Affecting Hearing Aid Performance* (2nd ed., pp. 205-220). Boston: Allyn and Bacon.

Humes, L. E. (1996). Speech understanding in the elderly. *J Am Acad Audiol, 7*(3), 161-167.

Humes, L. E. (2002). Factors underlying the speech-recognition performance of elderly hearing-aid wearers. *J Acoust Soc Am, 112*(3 Pt 1), 1112-1132.

Humes, L. E., Christensen, L., Thomas, T., Bess, F. H., Hedley-Williams, A., & Bentler, R. (1999). A comparison of the aided performance and benefit provided by a linear and a two-channel wide dynamic range compression hearing aid. *J Speech Lang Hear Res, 42*(1), 65-79.

Humes, L. E., & Christopherson, L. (1991). Speech identification difficulties of hearing-impaired elderly persons: the contributions of auditory processing deficits. *J Speech Hear Res, 34*(3), 686-693.

Humes, L. E., Dirks, D. D., Bell, T. S., Ahlstrom, C., & Kincaid, G. E. (1986). Application of the Articulation Index and the Speech Transmission Index to the recognition of speech by normal-hearing and hearing-impaired listeners. *J Speech Hear Res, 29*(4), 447-462.

Humes, L. E., & Roberts, L. (1990). Speech-recognition difficulties of the hearing-impaired elderly: the contributions of audibility. *J Speech Hear Res, 33*(4), 726-735.

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

Jenstad, L. M., Pumford, J., Seewald, R. C., & Cornelisse, L. E. (2000). Comparison of linear gain and wide dynamic range compression hearing aid circuits II: aided loudness measures. *Ear Hear, 21*(1), 32-44.

Jenstad, L. M., Seewald, R. C., Cornelisse, L. E., & Shantz, J. (1999). Comparison of linear gain and wide dynamic range compression hearing aid circuits: aided speech perception measures. *Ear Hear, 20*(2), 117-126.

Jenstad, L. M., & Souza, P. E. (2004). Quantifying the Effect of Wide-Dynamic-Range Compression on the Temporal Envelope of Speech in Noise, *Presentation at the IHCON conference, Lake Tahoe, California*.

Jenstad, L. M., & Souza, P. E. (2005). Quantifying the effect of compression hearing aid release time on speech acoustics and intelligibility. *Journal of Speech, Language, and Hearing Research, 48*(3).

Jusczyk, P. W., & Luce, P. A. (2002). Speech perception and spoken word recognition: past and present. *Ear Hear, 23*(1), 2-40.

Kiessling, J., Pichora-Fuller, M. K., Gatehouse, S., Stephens, D., Arlinger, S., Chisolm, T., Davis, A. C., Erber, N. P., Hickson, L., Holmes, A., Rosenhall, U., & von Wedel, H. (2003). Candidature for and delivery of audiological services: special needs of older people. *Int J Audiol, 42 Suppl 2*, 2S92-101.

Krause, J. C., & Braida, L. D. (2004). Acoustic properties of naturally produced clear speech at normal speaking rates. *J Acoust Soc Am, 115*(1), 362-378.

Larson, V. D., Williams, D. W., Henderson, W. G., Luethke, L. E., Beck, L. B., Noffsinger, D., Bratt, G. W., Dobie, R. A., Fausti, S. A., Haskell, G. B., Rappaport, B. Z., Shanks, J. E., & Wilson, R. H. (2002). A multi-center, double blind clinical trial comparing benefit from three commonly used hearing aid circuits. *Ear Hear, 23*(4), 269-276.

Lee, F. S., Matthews, L. J., Dubno, J. R., & Mills, J. H. (2005). Longitudinal study of pure-tone thresholds in older persons. *Ear Hear, 26*(1), 1-11.

Lindenberger, U., Scherer, H., & Baltes, P. B. (2001). The strong connection between sensory and cognitive performance in old age: not due to sensory acuity reductions operating during cognitive assessment. *Psychol Aging, 16*(2), 196-205.

Luce, P. A., & McLennan, C. (2003). *Fundamentals of spoken word recognition.* Paper presented at the Acoustical Society of America.

Luce, P. A., & Pisoni, D. B. (1998). Recognizing spoken words: the neighborhood activation model. *Ear Hear, 19*(1), 1-36.

Ludvigsen, C., Elberling, C., Keidser, G., & Poulsen, T. (1990). Prediction of intelligibility of non-linearly processed speech. *Acta Otolaryngol Suppl, 469*, 190-195.

Magnusson, L. (1996). Predicting the speech recognition performance of elderly individuals with sensorineural hearing impairment. A procedure based on the Speech Intelligibility Index. *Scand Audiol, 25*(4), 215-222.

Marslen-Wilson, W., & Tyler, L. K. (1980). Temporal structure of spoken language understanding. *Cognition, 8*(1), 1-71.

Moore, B. C. (1996). Perceptual consequences of cochlear hearing loss and their implications for the design of hearing aids. *Ear Hear, 17*(2), 133-161.

Moore, B. C., & Glasberg, B. R. (2004). A revised model of loudness perception applied to cochlear hearing loss. *Hear Res, 188*(1-2), 70-88.

Moore, B. C., Stainsby, T. H., Alcantara, J. I., & Kuhnel, V. (2004). The effect on speech intelligibility of varying compression time constants in a digital hearing aid. *Int J Audiol, 43*(7), 399-409.

Moore, B. C., Vickers, D. A., Plack, C. J., & Oxenham, A. J. (1999). Inter-relationship between different psychoacoustic measures assumed to be related to the cochlear active mechanism. *J Acoust Soc Am, 106*(5), 2761-2778.

Nabelek, A. K. (1988). Identification of vowels in quiet, noise, and reverberation: relationships with age and hearing loss. *J Acoust Soc Am, 84*(2), 476-484.

Nabelek, A. K. (1993). Communication in noisy and reverberant environments. In G. A. Studebaker & I. Hochberg (Eds.), *Acoustical Factors Affecting Hearing Aid Performance* (2nd ed.). Needham Heights, MA: Allyn & Bacon.

Nabelek, I. V. (1983). Performance of hearing-impaired listeners under various types of amplitude compression. *J Acoust Soc Am, 74*(3), 776-791.

Neuman, A. C., Bakke, M. H., Mackersie, C., Hellman, S., & Levitt, H. (1998). The effect of compression ratio and release time on the categorical rating of sound quality. *J Acoust Soc Am, 103*(5 Pt 1), 2273-2281.

Nittrouer, S., & Boothroyd, A. (1990). Context effects in phoneme and word recognition by young children and older adults. *J Acoust Soc Am, 87*(6), 2705-2715.

Ohde, R. N., & Abou-Khalil, R. (2001). Age differences for stop-consonant and vowel perception in adults. *J Acoust Soc Am, 110*(4), 2156-2166.

Ohde, R. N., & Stevens, K. N. (1983). Effect of burst amplitude on the perception of stop consonant place of articulation. *J Acoust Soc Am, 74*(3), 706-714.

Olsen, H. L., Olofsson, A., & Hagerman, B. (2004). The effect of presentation level and compression characteristics on sentence recognition in modulated noise. *Int J Audiol, 43*(5), 283-294.

Payton, K. L., & Braida, L. D. (1999). A method to determine the speech transmission index from speech waveforms. *J Acoust Soc Am, 106*(6), 3637-3648.

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *J Acoust Soc Am, 97*(1), 593-608.

Plomp, R. (1988). The negative effect of amplitude compression in multichannel hearing aids in the light of the modulation-transfer function. *J Acoust Soc Am*, *83*(6), 2322-2327.

Plomp, R. (1994). Noise, amplification, and compression: considerations of three main issues in hearing aid design. *Ear Hear, 15*(1), 2-12.

Plyler, P. N., & Hedrick, M. S. (2002). Effects of stimulus presentation level on stop consonant identification in normal-hearing and hearing-impaired listeners. *J Am Acad Audiol, 13*(3), 154-159.

Price, P. J., & Simon, H. J. (1984). Perception of temporal differences in speech by "normal-hearing" adults: effects of age and intensity. *J Acoust Soc Am, 76*(2), 405-410.

Repp, B. H. (1979). Relative Amplitude of Aspiration Noise as a Voicing Cue for Syllable Initial Stop Consonants. *Language and Speech, 22*(APR-), 173-189.

Robles, L., & Ruggero, M. A. (2001). Mechanics of the mammalian cochlea. *Physiol Rev, 81*(3), 1305-1352.

Rosen, S. (1989). Temporal information in speech and its relevance for cochlear implants, *Proceedings of the conference: Cochlear Implant: Acquisitions and controversies*.

Rosen, S., Faulkner, A., & Reeve, K. (1994). Voicing, fundamental frequency, amplitude envelope and voiceless excitation as cues to consonant identity. *Speech Hearing and Language; Work in Progress, Dept. Phonetics and Linguistics, University College London, 8*, 235-241.

Rosen, S., Faulkner, A., & Smith, D. A. (1990). The psychoacoustics of profound hearing impairment. *Acta Otolaryngol Suppl, 469*, 16-22.

Salasoo, A., & Pisoni, D. B. (1985). Interaction of knowledge sources in spoken word identification. *Journal of Memory and Language, 24*(2), 210-231.

Sammeth, C., Tetzeli, M., & Marleen, T. O. (1996). Consonant recognition performance of hearing-impaired listeners using one linear and three nonlinear hearing aids. *J Am Acad Audiol, 7*, 240-250.

Schneider, B. (2001). Sensation, Cognition, and Levels of Processing in Aging. In M. Naveh-Benjamin & M. Moscovitch & H. L. Roediger (Eds.), *Perspectives on Human Memory and Cognitive Aging: Essays in Honour of Fergus Craik* (pp. 298-314). New York: Psychology Press.

Schneider, B., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. Craik & T. A. Salthouse (Eds.), *The Handbook of Aging and Cognition* (2nd ed., pp. 155-220). Mahwah, New Jersey: Lawrence Erlbaum.

Schneider, B., Speranza, F., & Pichora-Fuller, M. K. (1998). Age-related changes in temporal resolution: envelope and intensity effects. *Can J Exp Psychol, 52*(4), 184-191.

Schneider, B. A., Daneman, M., Murphy, D. R., & See, S. K. (2000). Listening to discourse in distracting settings: The effects of aging. *Psychology and Aging, 15*(1), 110-125.

Schum, D. J., Matthews, L. J., & Lee, F. S. (1991). Actual and predicted word-recognition performance of elderly hearing-impaired listeners. *J Speech Hear Res, 34*(3), 636-642.

Shaddock Palombi, P., Backoff, P. M., & Caspary, D. M. (2001). Responses of young and aged rat inferior colliculus neurons to sinusoidally amplitude modulated stimuli. *Hear Res, 153*(1-2), 174-180.

Shannon, R. V. (2002). The relative importance of amplitude, temporal, and spectral cues for cochlear implant processor design. *Am J Audiol, 11*(2), 124-127.

Shannon, R. V., Zeng, F.-G., & Wygonski, J. (1992). Speech recognition using only temporal cues. In M. E. H. Schouten (Ed.), *The Auditory processing of speech: from sounds to words edited by M.E.H. Schouten* (pp. 380). Berlin; New York: Mouton de Gruyter.

Shannon, R. V., Zeng, F. G., Kamath, V., Wygonski, J., & Ekelid, M. (1995). Speech recognition with primarily temporal cues. *Science, 270*(5234), 303-304.

Sherbecoe, R. L., & Studebaker, G. A. (2003). Audibility-index predictions of normal-hearing and hearing-impaired listeners' performance on the connected speech test. *Ear Hear*, *24*(1), 71-88.

Shinn, P., & Blumstein, S. E. (1984). On the role of the amplitude envelope for the perception of [b] and [w]. *J Acoust Soc Am, 75*(4), 1243-1252.

Sommers, M. S., & Danielson, S. M. (1999). Inhibitory processes and spoken word recognition in young and older adults: the interaction of lexical competition and semantic context. *Psychol Aging, 14*(3), 458-472.

Sommers, M. S., Kirk, K. I., & Pisoni, D. B. (1997). Some considerations in evaluating spoken word recognition by normal-hearing, noise-masked normal-hearing, and cochlear implant listeners. I: The effects of response format. *Ear Hear, 18*(2), 89-99.

Souza, P. E. (2000). Older listeners' use of temporal cues altered by compression amplification. *J Speech Lang Hear Res, 43*(3), 661-674.

Souza, P. E., & Bishop, R. D. (1999). Improving speech audibility with wide dynamic range compression in listeners with severe sensorineural loss. *Ear Hear, 20*(6), 461-470.

Souza, P. E., & Bishop, R. D. (2000). Improving audibility with nonlinear amplification for listeners with high-frequency loss. *J Am Acad Audiol, 11*(4), 214-223.

Souza, P. E., Jenstad, L. M., & Boike, K. T. (submitted). Measuring the acoustic effects of compression amplification on speech in noise.

Souza, P. E., & Kitch, V. (2001). The contribution of amplitude envelope cues to sentence identification in young and aged listeners. *Ear Hear*, *22*(2), 112-119.

Souza, P. E., & Turner, C. W. (1996). Effect of single-channel compression on temporal speech information. *J Speech Hear Res, 39*(5), 901-911.

Souza, P. E., & Turner, C. W. (1998). Multichannel compression, temporal cues, and audibility. *J Speech Lang Hear Res, 41*(2), 315-326.

Souza, P. E., & Turner, C. W. (1999). Quantifying the contribution of audibility to recognition of compression-amplified speech. *Ear Hear, 20*(1), 12-20.

Spector, A. A., Brownell, W. E., & Popel, A. S. (1999). Nonlinear active force generation by cochlear outer hair cell. *J Acoust Soc Am, 105*(4), 2414-2420.

Steeneken, H. J. M., & Houtgast, T. (1999). Mutual dependence of the octave-band weights in predicting speech intelligibility. *Speech Communication*, *28*(2), 109-123.

Steeneken, H. J. M., & Houtgast, T. (2002). Phoneme-group specific octave-band weights in predicting speech intelligibility. *Speech Communication*, *38*(3-4), 399-411.

Stone, M. A., & Moore, B. C. (1992). Syllabic compression: effective compression ratios for signals modulated at different rates. *Br J Audiol*, *26*(6), 351-361.

Strom, K. (2003). The HR 2003 Dispenser Survey. *The Hearing Review, 10*(6), 22 ff.

Stuart, A., & Phillips, D. P. (1996). Word recognition in continuous and interrupted broadband noise by young normal-hearing, older normal-hearing, and presbyacusic listeners. *Ear Hear, 17*(6), 478-489.

Studebaker, G. A. (1985). A "rationalized" arcsine transform. *J Speech Hear Res, 28*(3), 455-462.

Studebaker, G. A., Sherbecoe, R. L., McDaniel, D. M., & Gray, G. A. (1997). Age-related changes in monosyllabic word recognition performance when audibility is held constant. *J Am Acad Audiol, 8*(3), 150-162.

Tremblay, K., Kraus, N., McGee, T., Ponton, C., & Otis, B. (2001). Central auditory plasticity: changes in the N1-P2 complex after speech-sound training. *Ear Hear, 22*(2), 79-90.

Tremblay, K. L., Piskosz, M., & Souza, P. (2003). Effects of age and age-related hearing loss on the neural representation of speech cues. *Clin Neurophysiol, 114*(7), 1332-1343.

Tun, P. A. (1998). Fast noisy speech: age differences in processing rapid speech with background noise. *Psychol Aging, 13*(3), 424-434.

Tun, P. A., O'Kane, G., & Wingfield, A. (2002). Distraction by competing speech in young and older adult listeners. *Psychology and Aging, 17*(3), 453-467.

Tun, P. A., & Wingfield, A. (1999). One voice too many: Adult age differences in language processing with different types of distracting sounds. *Journals of Gerontology Series B-Psychological Sciences and Social Sciences, 54*(5), P317-P327.

Turner, C. W., Souza, P. E., & Forget, L. N. (1995). Use of temporal envelope cues in speech recognition by normal and hearing-impaired listeners. *J Acoust Soc Am, 97*(4), 2568-2576.

van Buuren, R. A., Festen, J. M., & Houtgast, T. (1999). Compression and expansion of the temporal envelope: evaluation of speech intelligibility and sound quality. *J Acoust Soc Am, 105*(5), 2903-2913.

Van Tasell, D. J. (1993). Hearing loss, speech, and hearing aids. *J Speech Hear Res, 36*(2), 228-244.

Van Tasell, D. J., Greenfield, D. G., Logemann, J. J., & Nelson, D. A. (1992). Temporal cues for consonant recognition: training, talker generalization, and use in evaluation of cochlear implants. *J Acoust Soc Am, 92*(3), 1247-1257.

Van Tasell, D. J., Soli, S. D., Kirby, V. M., & Widin, G. P. (1987). Speech waveform envelope cues for consonant recognition. *J Acoust Soc Am, 82*(4), 1152-1161.

Van Tasell, D. J., & Trine, T. D. (1996). Effects of single-band syllabic amplitude compression on temporal speech information in nonsense syllables and in sentences. *J Speech Hear Res, 39*(5), 912-922.

van Toor, T., & Verschuure, H. (2002). Effects of high-frequency emphasis and compression time constants on speech intelligibility in noise. *Int J Audiol, 41*(7), 379-394.

Verschuure, J., Benning, F. J., Van Cappellen, M., Dreschler, W. A., & Boeremans, P. P. (1998). Speech intelligibility in noise with fast compression hearing aids. *Audiology, 37*(3), 127-150.

Verschuure, J., Maas, A. J., Stikvoort, E., de Jong, R. M., Goedegebure, A., & Dreschler, W. A. (1996). Compression and its effect on the speech signal. *Ear Hear, 17*(2), 162-175.

Versfeld, N. J., & Dreschler, W. A. (2002). The relationship between the intelligibility of time-compressed speech and speech in noise in young and elderly listeners. *J Acoust Soc Am, 111*(1 Pt 1), 401-408.

Walton, J. P., Frisina, R. D., & O'Neill, W. E. (1998). Age-related alteration in processing of temporal sound features in the auditory midbrain of the CBA mouse. *Journal of Neuroscience, 18*(7), 2764-2776.

Walton, J. P., Simon, H., & Frisina, R. D. (2002). Age-related alterations in the neural coding of envelope periodicities. *J Neurophysiol, 88*(2), 565-578.

Wechsler, D. (1972). Wechsler Memory Scale Form I.New York: The Psychological Corporation.

Westermann, S. (1993). Signal processing in programmable hearing instruments: A challenge to the auditory system? In J. Beilin & G. Jensen (Eds.), *Recent Developments in Hearing Instrument Technology* (Vol. 15th Danavox Symposium, pp. 273-290). Scanticon, Kolding, DK: Danavox.

Willott, J. F. (1996). Anatomic and physiologic aging: a behavioral neuroscience perspective. *J Am Acad Audiol, 7*(3), 141-151.

Wingfield, A., & Ducharme, J. L. (1999). Effects of age and passage difficulty on listening-rate preferences for time-altered speech. *J Gerontol B Psychol Sci Soc Sci, 54*(3), P199-202.

Wingfield, A., Lindfield, K. C., & Goodglass, H. (2000). Effects of age and hearing sensitivity on the use of prosodic information in spoken word recognition. *J Speech Lang Hear Res, 43*(4), 915-925.

Wingfield, A., Poon, L. W., Lombardi, L., & Lowe, D. (1985). Speed of processing in normal aging: effects of speech rate, linguistic structure, and processing time. *J Gerontol, 40*(5), 579-585.

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

Wingfield, A., Tun, P. A., Koh, C. K., & Rosen, M. J. (1999). Regaining lost time: adult aging and the effect of time restoration on recall of time-compressed speech. *Psychol Aging, 14*(3), 380-389.

Appendix I. Low probability sentences from the Speech Perception in Noise (SPIN) test.

Form 1 - LP Subject ID #________ Test Condition: _________
Test Date: __________ Test Order: _____________

	Score
Miss White won’t think about the ***crack***	/6
He would think about the ***rag***	/5
The ***old man talked about*** the ***lungs***	/5
I was considering the ***crook***	/4
Bill might discuss the ***foam***	/4
Nancy didn’t discuss the ***skirt***	/4
Bob has discussed the ***splash***	/4
Ruth hopes he heard about the ***hips***	/6
She wants to talk about the ***crew***	/6
They had a ***problem with*** the ***cliff***	/5
You heard Jane called about the ***van***	/6
We could consider the ***feast***	/4
Bill heard we asked about the ***host***	/6
I had not thought about the ***growl***	/6
He should know about the ***hut***	/5
I’m glad you heard about the ***bend***	/6
You’re talking about the ***pond***	/4
Nancy had considered the ***sleeves***	/4
He can’t consider the ***crib***	/4
Tom discussed the ***hay***	/3
She’s glad Jane asked about the ***drain***	/6
Bill hopes Paul heard about the ***mist***	/6
We’re speaking about the ***toll***	/4
We spoke about the ***knob***	/4
I’ve spoken about the ***pile***	/4

Form 2 -LP Subject ID # ________ Test Condition: ____________
Test Date: __________ Test Order: _____________

	Score
Miss Black thought about the ***lap***	/5
Miss Black would consider the ***bone***	/5
Bob could have known about the ***spoon***	/6
He wants to ***talk about*** the ***risk***	/5
He heard they called about the ***lanes***	/6
She has known about the ***drug***	/5
I want to ***speak about*** the ***crash***	/5
I should have considered the ***map***	/5
Ruth must have known about the ***pie***	/6
The ***man should discuss*** the ***ox***	/4
They heard I called about the ***pet***	/6
Bill cannot consider the ***den***	/4
She hopes Jane called about the ***calf***	/6
Jane has a ***problem with*** the ***coin***	/5
Paul hopes she called about the ***tanks***	/6
The ***girl talked about*** the ***gin***	/4
Mary should think about the ***sword***	/5
Ruth could have discussed the ***wits***	/5
You had a ***problem with*** the ***blush***	/5
We have not discussed the ***steam***	/5
Tom is considering the ***clock***	/4
You should not speak about the ***braids***	/6
Peter should speak about the ***mugs***	/5
He has a ***problem with*** the ***oath***	/5
Tom won't consider the ***silk***	/4

Form 3 - LP   Subject ID #________   Test Condition: _________
Test Date: __________   Test Order: _____________

	Score
Mr. ***White*** ***discussed*** the ***cruise***	/4
Miss ***White*** ***thinks*** ***about*** the ***tea***	/5
He ***is*** ***thinking*** ***about*** the ***roar***	/5
She's ***spoken*** ***about*** the ***bomb***	/4
You ***want*** ***to*** ***talk*** ***about*** the ***ditch***	/6
We're ***discussing*** the ***sheets***	/3
Betty ***has*** ***considered*** the ***bark***	/4
Tom ***will*** ***discuss*** the ***swan***	/4
You'd ***been*** ***considering*** the ***geese***	/4
They ***were*** ***interested*** ***in*** the ***strap***	/5
He ***could*** ***discuss*** the ***bread***	/4
Jane ***hopes*** ***Ruth*** ***asked*** ***about*** the ***stripes***	/6
Paul ***spoke*** ***about*** the ***pork***	/4
Mr. ***Smith*** ***thinks*** ***about*** the ***cap***	/5
We ***are*** ***speaking*** ***about*** the ***prize***	/5
Harry ***had*** ***thought*** ***about*** the ***logs***	/5
Bob ***could*** ***consider*** the ***pole***	/4
Ruth ***has*** a ***problem*** ***with*** the ***joints***	/5
He ***is*** ***considering*** the ***throat***	/4
We ***can't*** ***consider*** the ***wheat***	/4
The ***man*** ***spoke*** ***about*** the ***clue***	/4
David ***has*** ***discussed*** the ***dent***	/4
Bill ***heard*** ***Tom*** ***called*** ***about*** the ***coach***	/6
Jane ***has*** ***spoken*** ***about*** the ***chest***	/5
Mr. ***White*** ***spoke*** ***about*** the ***firm***	/5

Form 4 -LP Subject ID # ________ Test Condition: ___________
Test Date: __________ Test Order: _____________

	Score
Mary had considered the ***spray***	/4
The ***woman talked about*** the ***frogs***	/4
Miss Brown will speak about the ***grin***	/6
Bill can't have considered the ***wheels***	/5
Mr. Smith spoke about the ***aid***	/5
He hears she asked about the ***deck***	/6
You want to think about the ***dime***	/6
You've considered the ***seeds***	/3
Ruth's grandmother discussed the ***broom***	/4
Miss Smith considered the ***scare***	/4
Peter has considered the ***mat***	/4
The ***old man considered*** the ***kick***	/4
Paul could not consider the ***rim***	/5
I've been considering the ***crown***	/4
We've spoken about the ***truck***	/4
Mary could not discuss the ***tack***	/5
Harry might consider the ***beef***	/4
We're glad Bill heard about the ***ash***	/6
Nancy should consider the ***fist***	/4
They did not discuss the ***screen***	/5
The ***old man thinks about*** the ***mast***	/5
Paul wants to speak about the ***bugs***	/6
You're glad she called about the ***bowl***	/6
Miss Black could have discussed the ***rope***	/6
I hope Paul asked about the ***mate***	/6

Form 5 -LP Subject ID # ________ Test Condition: ___________
Test Date: __________ Test Order: _____________

	Score
Betty ***knew*** ***about*** the ***nap***	/4
The ***girl*** ***should*** ***consider*** the ***flame***	/4
They ***heard*** ***I*** ***asked*** ***about*** the ***bet***	/6
Mary ***knows*** ***about*** the ***rug***	/4
He ***was*** ***interested*** ***in*** the ***hedge***	/5
Jane ***did*** ***not*** ***speak*** ***about*** the ***slice***	/6
Mr. ***Brown*** ***can't*** ***discuss*** the ***slot***	/5
Paul ***can't*** ***discuss*** the ***wax***	/4
Miss ***Brown*** ***shouldn't*** ***discuss*** the ***sand***	/5
David ***might*** ***consider*** the ***fun***	/4
She ***wants*** to ***speak*** ***about*** the ***ant***	/5
He ***hasn't*** ***considered*** the ***dart***	/4
We've ***been*** ***discussing*** the ***crates***	/4
We've ***been*** ***thinking*** ***about*** the ***fan***	/5
Jane ***didn't*** ***think*** ***about*** the ***brook***	/5
Betty ***can't*** ***consider*** the ***grief***	/4
Harry ***will*** ***consider*** the ***trail***	/4
Tom ***is*** ***talking*** ***about*** the ***fee***	/5
Tom ***had*** ***spoken*** ***about*** the ***pill***	/5
Tom ***has*** ***been*** ***discussing*** the ***beads***	/5
Tom ***could*** ***have*** ***thought*** ***about*** the ***sport***	/6
Mary ***can't*** ***consider*** the ***tide***	/4
He ***hopes*** ***Tom*** ***asked*** ***about*** the ***bar***	/6
We ***could*** ***discuss*** the ***dust***	/4
Paul ***hopes*** ***we*** ***heard*** ***about*** the ***loot***	/6

Form 6 - LP Subject ID #________ Test Condition:__________
Test Date: __________ Test Order: _____________

	Score
You ***were*** ***considering*** the ***gang***	/4
The ***boy*** ***had*** ***considered*** the ***mink***	/4
He ***wants*** to ***know*** ***about*** the ***rib***	/5
She ***might*** ***have*** ***discussed*** the ***ape***	/5
The ***old*** ***woman*** ***discussed*** the ***thief***	/4
You ***are*** ***interested*** ***in*** the ***scream***	/5
We ***hear*** ***they*** ***asked*** ***about*** the ***shed***	/6
I ***haven’t*** ***discussed*** the ***sponge***	/4
Ruth ***will*** ***consider*** the ***herd***	/4
The ***old*** ***man*** ***discussed*** the ***dive***	/4
The ***class*** ***should*** ***consider*** the ***flood***	/4
I’m ***talking*** ***about*** the ***bench***	/4
Paul ***has*** ***discussed*** the ***lap***	/4
You ***knew*** ***about*** the ***clip***	/4
She ***might*** ***consider*** the ***pool***	/4
Bob ***was*** ***considering*** the ***clerk***	/4
The ***man*** ***knew*** ***about*** the ***spy***	/4
The ***class*** ***is*** ***discussing*** the ***wrist***	/4
They ***hope*** ***he*** ***heard*** ***about*** the ***rent***	/6
Mr. ***White*** ***spoke*** ***about*** the ***jail***	/5
Miss ***Brown*** ***might*** ***consider*** the ***coast***	/5
Bill ***didn’t*** ***discuss*** the ***hen***	/4
The ***boy*** ***might*** ***consider*** the ***trap***	/4
He ***should*** ***consider*** the ***roast***	/4
Miss ***Brown*** ***spoke*** ***about*** the ***cave***	/5

Form 7 -LP Subject ID # ________ Test Condition: ___________
Test Date: __________ Test Order: _____________

	Score
We're ***considering*** the ***brow***	/3
I ***am*** ***thinking*** ***about*** the ***knife***	/5
They've ***considered*** the ***sheep***	/3
He's ***glad*** ***we*** ***heard*** ***about*** the ***skunk***	/6
The ***girl*** ***should*** ***not*** ***discuss*** the ***gown***	/5
Mr. ***Smith*** ***knew*** ***about*** the ***bay***	/5
We ***did*** ***not*** ***discuss*** the ***shock***	/5
Mr. ***Black*** ***has*** ***discussed*** the ***cards***	/5
Mr. ***Black*** ***considered*** the ***fleet***	/4
We ***are*** ***considering*** the ***cheers***	/4
Sue ***was*** ***interested*** ***in*** the ***bruise***	/5
Miss ***Smith*** ***couldn't*** ***discuss*** the ***row***	/5
I'm ***discussing*** the ***task***	/3
Paul ***should*** ***know*** ***about*** the ***net***	/5
Miss ***Smith*** ***might*** ***consider*** the ***shell***	/5
You ***cannot*** ***have*** ***discussed*** the ***grease***	/5
I ***did*** ***not*** ***know*** ***about*** the ***chunks***	/6
I ***should*** ***have*** ***known*** ***about*** the ***gum***	/6
Mary ***hasn't*** ***discussed*** the ***blade***	/4
Ruth ***has*** ***discussed*** the ***peg***	/4
We ***have*** ***not*** ***thought*** ***about*** the ***hint***	/6
The ***old*** ***man*** ***discussed*** the ***yell***	/4
They're ***glad*** ***we*** ***heard*** ***about*** the ***track***	/6
The ***boy*** ***can't*** ***talk*** ***about*** the ***thorns***	/5
Bill ***won't*** ***consider*** the ***brat***	/4

Form 8 -LP Subject ID # ________ Test Condition: ___________
Test Date: __________ Test Order: _____________

	Score
Bob heard Paul called about the ***strips***	/6
Paul has a ***problem with*** the ***belt***	/5
They knew about the ***fur***	/4
We're glad Ann asked about the ***fudge***	/6
Jane was interested in the ***stamp***	/5
Miss White would consider the ***mold***	/5
They want to ***know about*** the ***aim***	/5
The ***woman discussed*** the ***grain***	/3
You hope they asked about the ***vest***	/6
We should have considered the ***juice***	/5
The ***woman considered*** the ***notch***	/3
The ***woman knew about*** the ***lid***	/4
Jane wants to ***speak about*** the ***chip***	/5
Bob should not consider the ***mice***	/5
Ruth hopes she called about the ***junk***	/6
I can't consider the ***plea***	/4
Paul was interested in the ***sap***	/5
He's glad you called about the ***jar***	/6
Miss Smith knows about the ***tub***	/5
The ***man could not discuss*** the ***mouse***	/5
Ann was interested in the ***breath***	/5
You're glad they heard about the ***slave***	/6
The ***man could consider*** the ***spool***	/4
Peter knows about the ***raft***	/4
She hears Bob asked about the ***cork***	/6

Vita

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Doctor of Philosophy in Audiology July 2005
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Postdoctoral Fellowship – *Canadian Institutes of Health Research*	2001-2005
1% Graduate Student Merit Award – *University of Washington*	2002-2005
ASH Foundation Student Research Grant in Audiology	2001
Postgraduate Scholarship - *NSERC* (declined)	2001
Leading Graduating Academician Award – *The University of Western Ontario*	1996
Leading Audiology Student Award – *The University of Western Ontario*	1995
Seminars on Audition Scholarship	1995
Special University Scholarship – *The University of Western Ontario*	1994-1995
Dean's Special Award – *Queen's University*	1992
The Annie Bentley Lillie Book Prize in Calculus – *Queen's University*	1992
Queen's University Honor Matriculation Scholarship	1988

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PEER-REVIEWED PUBLICATIONS:

Jenstad, L.M. & Souza, P.E. (2005). Quantifying the effect of hearing aid release time on speech acoustics and intelligibility, *Journal of Speech-Language-Hearing Research, 48(*3*).*

Souza, P.E., Jenstad, L.M., & Folino, R. (2005). Using multichannel WDRC in severely impaired listeners: Effects on speech recognition and quality, *Ear and Hearing, 26*(2): 120-131.

Jenstad, L.M., Van Tasell, D., & Ewert, C.M. (2003). Hearing aid troubleshooting based on patients' descriptors. *Journal of the American Academy of Audiology, 14(*7*)*: 347-361.

Jenstad, L.M., Pumford, J., Seewald, R.C. & Cornelisse, L.E. (2000) Comparison of linear gain and wide-dynamic-range compression (WDRC) hearing aid circuits: Aided loudness measures. *Ear and Hearing, 21(*1*): 32-44*.

Pumford, J., Seewald, R.C., Scollie, S.D. & Jenstad, L.M. (2000) Speech recognition in diffuse noise using in-the-ear and behind-the-ear dual-microphone hearing instruments. *Journal of American Academy of Audiology, 11:* 23-35.

Jenstad, L.M., Seewald, R.C., Cornelisse, L.E. & Shantz, J. (1999) Comparison of linear gain and wide-dynamic-range compression hearing aid circuits: Aided speech perception measures. *Ear and Hearing, 20*(2): 117-126.

Scollie, S.D., Seewald, R.C., Cornelisse, L.E. & Jenstad, L.M. (1998) Validity and repeatability of level-independent HL to SPL transforms. *Ear and Hearing, 19*(5): 407-413.

Jenstad, L.M., Cornelisse, L.E. & Seewald, R.C. (1997) Effects of test procedure on individual loudness functions. *Ear and Hearing, 18*(5): 401-408.