ABSTRACT

Title of Document: AGE-RELATED EFFECTS ON THE THRESHOLD EQUALIZING NOISE (TEN) TEST

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Some individuals with sensorineural hearing loss have certain places along the basilar membrane where inner hair cells and/or neurons are damaged or destroyed and consequently have ceased to function. These regions have been referred to as "dead regions" in the literature. The TEN (HL) test is a relatively quick behavioral test designed to identify cochlear dead regions. The test relies on the detection of pure-tone signals in the presence of a specially designed broadband noise (threshold equalizing noise) masker. The TEN (HL) test was validated on young to middle aged adult listeners, an age group which does not represent that of all adults with hearing loss. The goal of this study was to evaluate the effects of age on the TEN (HL) test. The TEN (HL) test was administered to 18 younger and 18 older adults with normal to near-normal hearing sensitivity at seven different frequencies in three different levels of TEN noise. These measures were conducted twice to assess test re-test reliability. The older group demonstrated significantly poorer (higher) SNRs compared to the younger group at all three TEN noise levels and for all seven test frequencies. The greatest difference between groups was observed for the highest level of TEN noise. The greatest difference in SNRs was at 4000 Hz compared to other test frequencies for both groups. Both groups

performed best (lowest SNRs) at 4000 Hz compared to the other test frequencies. Finally, a main effect of trial was found, revealing that both groups performed statistically better (lower SNRs) on the second trial; however the small magnitude of this improvement (0.37 dB), suggests that the TEN (HL) test has good repeatability for clinical use, at least within the time period assessed. Although there were significant differences between the two groups, overall the TEN (HL) test yielded accurate results in classifying all normal to near-normal hearing participants as not having a dead region. The significantly higher (poorer) SNRs associated with age, combined with the expected difference in SNRs associated with hearing loss, may allow for older hearing-impaired individuals to demonstrate abnormally high SNRs on the TEN (HL) test in the absence of a cochlear dead region. Future studies that include younger and older participants with normal hearing and hearing loss are needed to assess these differences and examine whether different norms are needed for this older population.

AGE-RELATED EFFECTS ON THE THRESHOLD EQUALIZING NOISE (TEN) TEST

By

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Dedication

This dissertation is dedicated to all my family and friends who have supported me throughout this process. Thank you to my parents for always being there for me and encouraging me to succeed. Special thanks to Mook for his love, encouragement, patience, support, and ability to always make me laugh. Finally, I wish to thank my classmates, Caroline, Erin, Kelly, Krystal, and Lauren for their friendship and support.

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Chapter 1: Introduction

Some individuals with sensorineural hearing loss have certain places along the basilar membrane where inner hair cells and/or neurons are damaged or destroyed. These regions have been referred to as “cochlear dead regions” or “dead regions” in the literature (Moore & Glasberg, 1997). Presumably, the inner hair cells have ceased to function in these regions, resulting in a loss of stimulation to the auditory nerve. As a result, a stimulating tone corresponding to the characteristic frequency of that region is detected by off-place listening (Moore, 2004; Moore, Glasberg & Stone, 2004). Traditionally, dead regions were measured in laboratories or research settings using psychophysical tuning curves (PTCs). In 2000, Moore, Huss, Vickers, Glasberg and Alcantara developed a quicker behavioral test of auditory function, the “Threshold Equalizing Noise (TEN) Test,” that could be utilized in a clinical setting to identify cochlear dead regions and define their boundaries. This test relies on the detection of pure-tone signals in the presence of a specially designed broadband noise (threshold equalizing noise) masker (Moore et al., 2000).

Some research has suggested that the TEN test may not be as sensitive and specific a measure for the identification of dead regions as more established measures such as PTCs (e.g., Summers, Molis, Musch, Walden, Surr & Cord, 2003). Nevertheless, this same research illustrated the problems associated with the measurement of PTCs in the identification of dead regions; mainly, that they are too time consuming for routine clinical use, and results may be influenced by combination tone detection (Moore, 2004; Moore, et al., 2000; Summers, et al., 2003). Recent studies (Aazh & Moore, 2007; Cairns, Frith, Munro & Moore, 2007; Mackersie, Crocker & Davis, 2004; Moore, Killen

& Munro, 2003; Munro, Felthouse, Moore & Kapadia, 2005; Preminger, Carpenter & Ziegler, 2005; Vinay & Moore, 2007) appear to accept the TEN test as valid for the identification of dead regions.

Two versions of the TEN test have been developed, with the original version providing measurements in dB sound-pressure level (dB SPL) and the new version providing measurements in dB hearing level (dB HL). Both versions are designed to assess whether or not patients have dead regions. Most of the studies published thus far have employed the TEN (SPL) version of the test. Recent studies (Aazh & Moore, 2007; Cairns et al., 2007; Vinay & Moore, 2007) have started utilizing the TEN (HL) version.

The TEN (HL) version was validated on young to middle aged adult listeners (aged 23-54 years), an age group which does not represent that of all adults with hearing loss (Moore et al., 2004). Research has demonstrated that younger listeners and older listeners perform differently on many auditory tasks presented in noise (Burkard & Sims, 2002; Dubno, Horwitz & Ahlstrom, 2002; Gifford & Bacon, 2005; Patterson, Nimmo-Smith, Weber & Milroy, 1982; Potash & Jones, 1977; Rees & Botwinick, 1971). Thus, the normative data of the TEN test, obtained with younger individuals, may not generalize to older listeners. For example, frequency selectivity differences between younger and older listeners have been demonstrated in the literature and may account for some of the variations between the two groups (Patterson et al., 1982). Older listeners often have excessive difficulty listening to signals in noise, and it is possible that their performance on the TEN test will be poor, even in the absence of dead regions. Research has demonstrated that “detection efficiency” or “processing efficiency” worsens with increasing age (Gifford & Bacon, 2005; Patterson et al., 1982; Peters & Moore, 1992).

Because the current normative data for the TEN test were based on the responses of young to middle-aged adult listeners, it is possible that new age-appropriate normative data may be needed for the determination of cochlear dead regions in older adult listeners.

The primary goal of this study is to determine if there are age-related differences between young listeners with normal hearing and older listeners with normal hearing on the TEN (HL) test. Another goal of the study is to assess if the level of the TEN noise employed, test frequency, or test trial have a differential effect on the signal-to-noise ratios observed for younger normal-hearing listeners compared to older normal-hearing listeners. It is expected that older normal-hearing listeners will demonstrate higher signal-to-noise ratios than those observed for young normal-hearing listeners. Further, it is expected that older normal-hearing listeners will demonstrate the highest signal-to-noise ratios when the highest level of the TEN noise is presented. Consequently, a finding of age-related differences on the TEN (HL) test may indicate that new age-appropriate criteria for determining dead regions for older hearing listeners are needed.

Chapter 2: Literature Review

Hair Cell Functioning

Roles of functional and nonfunctional IHCs and OHCs.

Hearing is a complicated process, involving a large number of specialized physiological structures. The inner and outer hair cells of a healthy cochlea have important functions in the hearing process and their structure and organization have been described in the literature (Lim, 1980, 1986). Outer hair cells (OHCs) are responsible for increasing the vibration of the basilar membrane in response to soft sounds and for sharpening tuning along the basilar membrane (Liberman & Dodds, 1984; Ruggero, 1992; Smith, Moody, Stebbins, & Norat, 1987). The OHCs are believed to be responsible for actively amplifying input to the inner hair cells (IHCs) through biological processes (Neely & Kim, 1986). The OHCs accomplish this, according to one model (Patuzzi, Yates, & Johnstone, 1989), by increasing the amplitude of the basilar membrane vibration at a certain place on the basilar membrane that is tonotopically organized to respond best to that particular frequency. The inner hair cells (IHCs) are responsible for converting the vibration of the basilar membrane into action potentials by directly stimulating the afferent neurons comprising the auditory nerve (Ruggero, 1992). Therefore, the OHCs and IHCs in a healthy cochlea play an important role in the transduction of an acoustic signal into action potentials in the auditory nerve.

Cochlear hearing loss is often associated with damage to both the OHCs and the IHCs resulting in reduced OHC and IHC function (Moore et al., 2000; Moore, 2004; Schuknect & Gacek, 1993). Complete loss of OHCs does not necessarily equate with a complete loss of hearing; however, absolute thresholds likely will be elevated. The reduction of OHC function means that the active mechanism in the cochlea responsible for responding to low level sounds is impaired, resulting in reduced basilar membrane vibration. This, in turn, results in elevated audiometric thresholds, because soft sounds must be more intense in order to produce the same response on the basilar membrane as in a healthy cochlea (Moore et al., 2000; Van Tassell, 1993).

Based on information gained in studies of OHC function in the guinea pig (Patuzzi et al., 1989) it can be predicted that hearing losses of approximately 55 dB HL in humans can be attributed to damage to OHCs. When hearing losses are greater than 55 to 60 dB HL, they typically involve IHC damage and/or loss (Van Tassell, 1993; Yates, 1990). Sensorineural hearing loss can result from the complete loss of IHCs with no loss of neurons, or visa versa. On a functional level, if the IHCs are damaged, or completely destroyed, transduction of the signal from the basilar membrane to the auditory nerve will not be as efficient as normal in the damaged region (Yates, 1990). This would result in reduced information about the signal being transmitted to the brain.

If the IHCs are still functioning, it is possible that either synaptic transmission to auditory neurons or the auditory neurons themselves are abnormal. In either case, the result is "noisy" transmission along the auditory nerve. It has been suggested that this "noisy" transmission may contribute to poorer word recognition ability often observed clinically in individuals with sensorineural hearing loss (Moore, 2004; Vickers, Moore & Baer, 2001). One theory stipulates that when the loss of IHCs and/or neurons is greater than approximately 50%, discrimination of different sounds, including speech, may be difficult (Schuknect & Gacek, 1993). Typically, audiometric thresholds are not affected by neuronal loss until more than 80-90% of the neurons are damaged or destroyed completely (Schuknecht & Gacek, 1993; Schuknect & Woellner, 1953).

For some individuals, the damage or destruction of IHCs along the basilar membrane can result in non-functioning areas, or regions, along the basilar membrane. These non-functioning areas of IHCs and/or neurons along the basilar membrane have been termed "dead regions" (Moore & Glasberg, 1997).

Cochlear dead regions

As defined previously, a dead region is a region of the basilar membrane where IHCs and/or neurons are non-functioning or destroyed, and the frequency selectivity of this region is reduced. Consequently, the IHCs and/or neurons in this region will no longer respond efficiently to tones that should be detected by this region. However, if the tone is presented at an intense level, the spread of excitation along the basilar membrane (either apically or basally depending on the frequency of the signal) may still allow for this tone to be detected (Moore, 2004).

A healthy cochlea is believed to have the ability to analyze different frequencies based on the tonotopic organization of the basilar membrane. Each place along the basilar membrane is sharply tuned to respond best to a specific frequency. This specific frequency is called the characteristic frequency (CF) or best frequency of the auditory neurons (Liberman, 1982). Liberman (1982) derived a map ("cochlear frequency map") demonstrating this tuning along the basilar membrane by tracing the path (using horseradish peroxidase) from the auditory neurons to the characteristic frequency along the basilar membrane in cats (Liberman, 1982).

A dead region is identified by a shift in the characteristic frequency (CF) than that expected for a specific region along the basilar membrane. For example, Moore et al. (2000) noted that if a dead region exists over a certain region, the basilar membrane vibration would not be detected by the neurons that are responsible for innervating that dead region. Instead, if the signal were sufficiently intense, it would be detected by neurons that innervate adjacent regions along the basilar membrane. For example, a high-frequency pure-tone is presented to a normal hearing ear, the basal region of the cochlea would stimulate neurons tuned best to that high frequency of the signal. If the IHCs and/or neurons in this same region are no longer functioning, no information will be transmitted from this high-frequency region. However, if this same pure tone is presented at a sufficiently intense level to produce spread of excitation along the basilar membrane, this high-frequency sound may be detected. In this case, the sound is detected by neurons that are tuned to lower frequencies (apical end). This has important implications for the measurement of audiometric thresholds. Although patients may respond to the presentation of pure tones at certain frequencies, if the IHCs and/or neurons are non-functioning over these same frequency regions, the audiogram may represent off-frequency listening. The patient responds to hearing a tone at these off-frequencies because the audiologist has presented the pure tone at an intense level, causing the IHCs or neurons of adjacent regions to be stimulated (Moore et al. 2000; Moore & Alcantara, 2001).

This phenomenon is commonly referred to as “off-place listening” or “off-frequency listening.” It is based on the idea that when a pure tone is presented at a sufficiently intense level, it causes spread of excitation of basilar membrane vibration at places other than just the CF of the tone. This results in detection of the pure tone by IHCs and/or neurons with CFs that are different from the presented pure tone. When these contributions become greater than those associated with the CFs of the signal, off-frequency listening is taking place. In this way, the true hearing sensitivity at the CF is not measured (Vestergaard, 2003). Off-frequency listening may contribute to audiograms reflecting hearing thresholds as low as 40 dB HL at frequencies where dead regions exist (Moore, 2001).

As discussed previously, for hearing losses greater than 55-60 dB HL, the OHCs are damaged, and the IHCs most likely become damaged as well (Liberman & Dodds, 1984; Ruggero et al., 1997; Yates, 1990). Moore (2001) suggested that a dead region could be accurately defined in terms of the CFs of the IHCs and/or neurons immediately adjacent to the dead region (Moore, 2001). According to this definition, for example, if IHCs are functioning normally for CFs corresponding to low frequencies up to 4000 Hz but then cease to function, the dead region would be defined as extending from 4000 Hz and higher.

Dead regions cannot be determined reliably from the audiogram due to off-frequency listening (Moore, 2004). In fact, two individuals could have identical audiograms but one may have a dead region and the other may not. This was supported by a post-mortem examination conducted by Halpin, Thornton, and Hasso (1994). In this study, the authors conducted post-mortem examinations of two individuals with similar audiograms. Audiometric data showed that both individuals had a low-frequency hearing loss with near-normal hearing sensitivity in the mid-frequency range. Upon post-mortem examination, one of the individuals had no organ of Corti in the apical region of the cochlea while the other had an intact organ of Corti that appeared to be normal (Halpin et al., 1994).

If identifying a dead region does not predict differences, or problems, for these individuals, then the identification of dead regions has no clinical value. Prior to the definition of dead regions, it was commonly observed in clinical practice that people with high-frequency moderate-to-severe sensorineural hearing losses did not always benefit from high-frequency amplification. For some of these individuals with hearing losses exceeding 50 dB HL, it was observed that providing high-frequency amplification (especially at 4000 Hz and above) actually resulted in poorer speech recognition scores (Hogan & Turner, 1998). Summers et al. (2003) commented that amplified sound in frequency regions corresponding to dead regions may be detected via spread of excitation to areas where the IHCs are functioning. Although this would allow for the hearing aid user to detect information in these regions, the frequency information would not be conveyed correctly in this region, potentially contributing to problems with clarity. This could have important implications for understanding speech. For example, for an individual with a high-frequency dead region, amplification provided by a hearing aid may amplify the sounds causing them to be intense enough for adjacent areas along the basilar membrane to detect the signals. The high-frequency information received by regions or nerve fibers that respond best to low-frequency information may cause distortion or interference in interpreting the signal. Further, speech information that should be conveyed by the frequencies corresponding to the high-frequency dead regions may not be processed efficiently in these regions tuned to lower frequencies (Summers et al., 2003).

Methods for assessing dead regions

One method used to assess dead regions is a psychophysical tuning curve (PTC) (Chistovich, 1957; Small, 1959). This method utilizes a procedure that is very similar to measuring a neural tuning curve. Measurement of PTCs involves detection of a signal that is fixed in frequency and level, in the presence of a masker, that can either be a pure-tone or a noise masker. The signal is typically presented approximately 10 dB sensation level (SL) re: the absolute threshold level for that frequency (Chitovich, 1957; Small, 1959). The masker most commonly employed in recent studies is a narrow band noise (Moore et al., 2001; Summers et al., 2003). Use of this masker can reduce the detection of beats between the signal and the masker (Moore, Alcantara & Dau, 1998) which occurs with a tone-on-tone masking paradigm. The actual measurement of PTCs requires determining the level of the masker needed to mask the signal for several different masker center frequencies.

The shape of the PTC is measured by plotting the masker level as a function of the masker frequency, using a logarithmic scale, for many different masker center frequencies. By presenting the signal at a low level (only 10 dB SL) it is assumed that the signal should innervate the neurons with CFs closest to the signal frequency (for ears with no dead regions). It is further assumed that the narrow band masker presented at threshold should produce a constant response in these same neurons, thereby masking the fixed signal. Therefore, as the masker gets closer in frequency to that of the test signal, the level required to mask the signal will become lower and lower. The resulting PTC typically shows a sharply tuned “tip” which represents the frequency where the lowest masker level was required to just mask the signal (Moore, 1978; Moore et al., 2000; Summers et al., 2003).

For normal hearing listeners, the tip of the PTC lies close to the signal frequency (Moore, 1978; Moore et al., 2000; Moore & Alcantara, 2001). This indicates that the masker is most effective when its center frequency is closest to the signal (Kluk & Moore, 2005; Moore & Alcantara, 2001; Summers et al., 2003). Similar results have also been demonstrated for individuals with sensorineural hearing loss of mild degree. In a study by Nelson (1991), PTCs of individuals with sensorineural hearing loss less than 40 dB HL were demonstrated to be similar to PTCs of individuals with normal hearing sensitivity when measured with probe tones of comparable levels (Nelson, 1991). Some studies have found PTCs where the tips were shifted away from the signal frequency (Moore et al., 2000; Moore & Alcantara 2001; Nelson, 1991). This occurs when the signal frequency corresponds to a CF that falls in a dead region.

In individuals who have dead regions, a higher- or lower- (depending on where the dead region is located in the cochlea) frequency masker will be more effective at masking the signal than a masker with the same frequency as the dead region, because of the spread of excitation. This spread of excitation results in the signal being detected by off-frequency listening (Kluk & Moore, 2005; Moore & Alcantara, 2001; Summers et al., 2003; Vestergaard 2003). The measurement of PTCs provides a way to determine the boundaries of dead regions in the cochlea. If an individual has a dead region, the PTC tip will be shifted away from the signal frequency in an obvious way. The masker frequency corresponding to the location of the tip of the PTC is assumed to be the boundary, or edge, of the dead region (Kluk & Moore 2005; Moore et al., 2000; Summers et al., 2003).

Although the measurement of PTCs is a well-established psychoacoustical method, it can present some problems for the identification of dead regions. The most obvious problem associated with measuring PTCs for the confirmation of dead regions is that it is a time consuming method and therefore, not practical for routine clinical practice (Moore et al., 2000; Moore, 2004). The measurement of PTCs can be affected by the detection of simple difference tones and the detection of beats in a tone-on-tone paradigm. These two phenomena can falsely lead to the measurement of a PTC tip close to, or at, a signal frequency when in fact that signal falls in a dead region (Moore, 2004).

Studies have shown that the signal and the masker can interact in the measurement of PTCs producing a combination tone that affects the results of the PTCs in a tone-on-tone paradigm (Greenwood, 1971). This combination of the signal and the masker may be easier for the individual to detect than the actual signal. For individuals with normal hearing, the detection of the cubic-difference tone (2f1-f2) can affect masked thresholds when the test signal has a frequency that is just above the masker frequency (Alcantara & Dau, 1998; Alcantara, Moore & Vickers, 2000). For individuals with cochlear hearing loss, this combination tone is not as easily detected and therefore does not affect the masked thresholds as much as for normal hearing listeners (Moore, 2004). When combination tones are detected during the measurement of PTCs, a sharp tip at the signal frequency (suggesting no dead region) can be observed, even though the signal actually falls in a dead region.

The overall shape and the exact frequency of the tip of PTCs can be affected by the detection of beats that occur between the signal and the masker, even if the masker employed is a narrow band masker (Moore et al., 2000). This beat detection could provide an additional cue that the signal frequency is present when the narrow band masker is presented just slightly below, or above, the signal frequency. The result is that the tip of the PTC is measured at the signal frequency even when the signal frequency falls within a dead region (Moore, 2004; Moore & Alcantara, 2001). In these situations, employing a different masking paradigm, such as a forward masking paradigm as opposed to a simultaneous masking paradigm, would alleviate some of these issues for determining PTCs (Kluk & Moore, 2006). Another strategy that has been suggested to address the detection of beats during the measurement of PTCs (with a simultaneous masking paradigm) is to employ a noise masker with a bandwidth that is similar to the bandwidth of the auditory filter for the PTC being measured (Kluk & Moore, 2005). Although PTCs are considered the "gold standard" (Summers et al., 2003) for detecting non-functioning regions of IHC's and/or neurons along the basilar membrane, the measurement of PTCs is too time consuming for routine clinical application.

Threshold equalizing noise (TEN) test

Moore et al. (2000) developed a new test for identifying cochlear dead regions called the "Threshold Equalizing Noise" (TEN) test. The original version of the TEN test was developed utilizing dB SPL measurements. The TEN test is based on the detection of pure-tone signals in the presence of a broadband noise masker that is fixed in level. The masking noise, "threshold-equalizing noise (TEN)," was altered spectrally to produce a broadband signal that would produce similar masked thresholds of pure tones across the frequency range 250-10,000 Hz for normal hearing listeners and hearing-impaired listeners with no dead regions. The spectrum and waveform of the TEN (HL) noise are illustrated in Figure 1. If an individual has a dead region, the TEN noise should cause the masked thresholds to be elevated compared to thresholds measured in quiet in the frequency region with dead regions (Moore et al., 2000; Moore et al., 2004). By increasing the intensity of the pure-tone signal over the TEN noise, which results in stimulating adjacent functioning inner hair cells, the individual is able to detect the signal due to “off-frequency listening.” In the presence of the TEN noise, the pure-tone signal will need to be more intense than the noise to be detected by these functioning adjacent regions, resulting in elevated masked thresholds above the level of the TEN noise (Vestergaard, 2003).

The level of the TEN noise is expressed according to the average Equivalent Rectangular Bandwidth (ERB) of the auditory filter of a young normal hearing listener (ERB_N) to sound levels that are moderate in degree. These ERBs are very similar to the concept of critical bands (Fletcher, 1940) in that they represent a rectangular filter centered around a specific frequency. More specifically, the ERB is described as a rectangular filter that passes the same amount of energy, or power, as would actually pass through the auditory filter (which has a rounded top and sloping edges). Moore et al. (2000) designed the TEN level to specify the level in a one-ERB_N (132 Hz) wide band that has a center frequency of 1000 Hz. The signal level at masked threshold is approximately equal to the noise level/ERB_N for normal hearing listeners (Moore et al., 2000; Moore, 2004). For example, if the noise level employed is 80 dB SPL/ERB_N, the masked thresholds measured should be close to 80 dB SPL with a standard deviation of 2-3 dB (Moore et al., 2000; Moore et al., 2004).

For normal hearing listeners, thresholds measured for pure-tone signals in the TEN noise are approximately equal (in dB SPL) over the 250-10,000 Hz frequency range

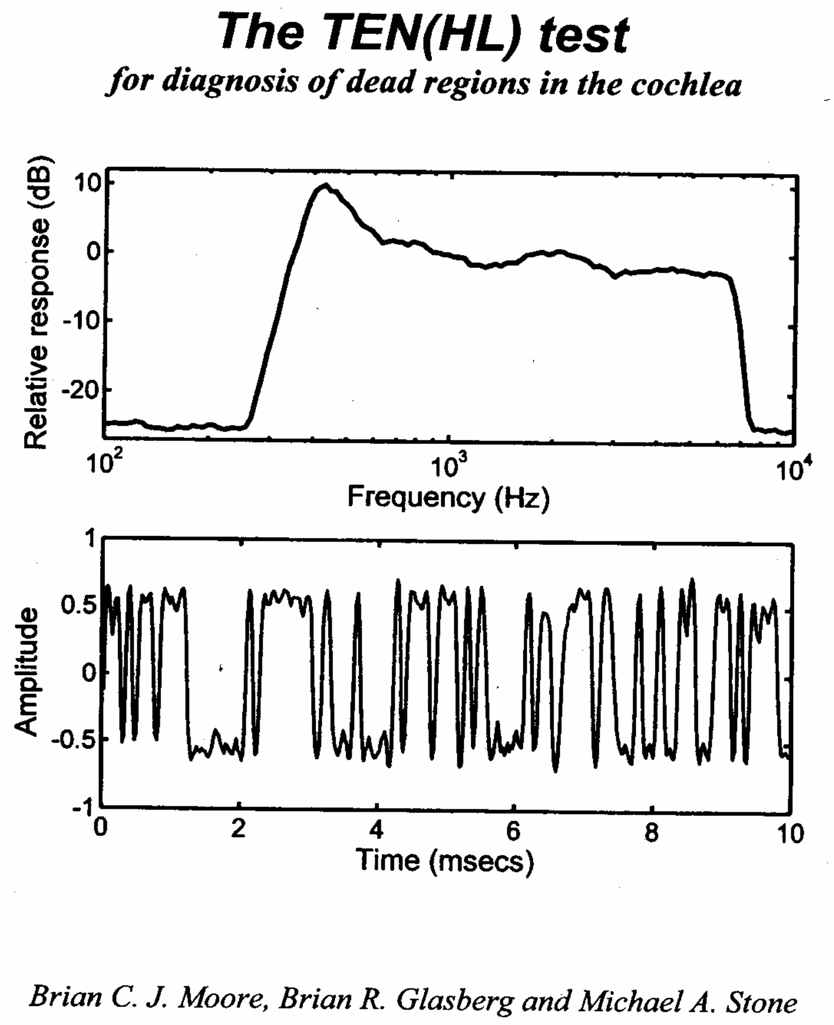

Figure 1. Spectrum and waveform of the TEN (HL) noise (Moore et al., 2004).

(Moore et al., 2000; Summers et al., 2003). In hearing-impaired listeners with no deadregions, the IHCs and/or neurons are still functioning even though measured thresholds are elevated at the frequencies where the individual demonstrates a hearing loss. For these individuals, the pure-tone signal is still detected by IHCs and/or neurons that have CFs that are the same, or very similar, to the frequency of the pure-tone signal. Therefore, both normal hearing listeners and hearing-impaired listeners with no dead regions detect the pure-tone signal using an auditory filter that has a CF close to the frequency of the pure-tone signal. It has been established that auditory filters tend to become broader with cochlear hearing loss (Glasberg & Moore, 1986; Peters & Moore, 1992). The broadening of auditory filters leads to a smaller signal-to-noise ratio of output at these pure-tone frequencies because more noise gets through the filter causing reduced detectability of the signal. The broader auditory filters associated with cochlear hearing loss do not appear to be more than five times larger than normal auditory filters (Moore & Glasberg, 1997).

If an individual has a dead region corresponding to the frequency of a signal, the signal will be detected via off-frequency listening when the signal is presented at an intense enough level (in quiet). Because the IHCs and/or neurons are non-functioning in the same frequency region as the signal, presentation of the TEN noise should produce a masked threshold that is considerably higher (above) than both the level of the TEN noise and the threshold measured in quiet (Moore, 2004). Because the greatest amplitude of basilar membrane displacement will be at an adjacent frequency region, the TEN noise will more effectively mask the tone because it only has to mask the remote place along the basilar membrane. This will cause an elevation in the measured masked threshold for this signal frequency, a result that is indicative of a dead region. It has been demonstrated that the TEN noise typically produces masked thresholds approximately 10 dB higher (above) than the level/ERB$_N$ of the TEN noise employed in cases with presumed dead regions (Moore et al., 2000; Summers et al., 2003).

To validate if the TEN test accurately identified dead regions, Moore et al. (2000) conducted a study that compared the results of the TEN test to results obtained by the more established method of PTCs for listeners with sensorineural hearing loss. Thresholds in quiet and masked thresholds using the TEN noise were measured in one ear for two different control groups of participants for the frequency range 250-8000 Hz (the latter group was tested at an extended range up to 10k Hz). The first control group consisted of 12 normal-hearing individuals and the second group consisted of 10 normal-hearing individuals that were "mostly different from those in the first group" (Moore et al., 2000). Normal hearing was defined as having absolute thresholds of 15 dB HL or better across test frequencies and no history of hearing disorders. Moore et al. (2000) did not report the gender, ages, or any additional descriptive factors associated with these control groups. The experimental group consisted of 14 participants (both ears of 6 participants were tested and one ear of 8 participants was tested, resulting in a total of 20 ears) ranging in age from 47-84 years, with varying amounts of sensorineural hearing loss (Moore et al., 2000).

According to Moore et al. (2000), the two control groups demonstrated similar results. For the three levels/ERB of TEN employed (30, 50, and 70 dB SPL) the masked thresholds were within 10 dB (ranging from +7 to +10 dB) of the level/ERB of TEN noise across frequencies for all participants in both control groups. The authors also conducted the TEN test and measured PTCs on 19 ears with identified sensorineural hearing loss. They found good correspondence between the TEN results and the PTCs for this experimental group, meaning that both measures yielded similar results. Of the 19 ears with moderate-to-severe sensorineural hearing loss, 13 had dead regions. The authors concluded that in frequency regions with hearing loss greater than 85 dB HL, a dead region was nearly always identified. Based on the comparison of results obtained with the TEN test and results obtained on PTC measures, the authors suggested some criteria for the identification of dead regions with the TEN (SPL) test. If the masked threshold is at least 10 dB above the threshold measured in quiet and 10 dB above the level/ERB of TEN, a dead region is suggested at this test frequency. The individuals who demonstrated this shift also showed a shift in the tip of their PTCs (the more established measure) (Moore et al., 2000; Moore, 2004).

In this study, the authors did not measure PTCs on the control groups to assess if there was good correspondence between the two measures among individuals with normal hearing. The authors stated there was "generally a good correspondence between the results of the PTC and TEN" measurements among the experimental participants, but they did not provide any statistical analysis of this "correspondence." The authors mentioned that in two of the 13 ears determined to have dead regions, the participants met the criteria for a dead region on the TEN test, but did not show a shift of the PTC tip, resulting in a false-positive identification (Moore et al, 2000).

Summers et al. (2003) also examined the consistency between the TEN test and PTC methods of identifying dead regions. Seventeen individuals (total of 18 ears) ranging in age from 59-76 years, with steeply sloping moderate-to-severe high-frequency sensorineural hearing loss participated in the study. In order to ensure that some of the participants would in fact have dead regions, all participants had thresholds less than or equal to 30 dB HL at 250 and 500 Hz with increased hearing loss (40 dB/octave) between 500 and 1500 Hz. The TEN test and PTCs (with signals presented at 10 dB SL and a noise masker of 100 Hz bandwidth) were measured for all participants. Results indicated that six ears out of 18 had dead regions on both PTC and TEN tasks and four ears showed no evidence of dead regions on either task. Of the remaining eight ears, the two tasks produced conflicting results at one or more frequencies tested; in these instances it was noted that the TEN results suggested the presence of dead regions while the PTC method did not. In total, six out of 18 ears (33%) demonstrated dead regions in this study on both measures. The authors suggest their results are in agreement with previous studies in that a subset of individuals with moderate-to-severe sensorineural hearing loss demonstrated dead regions. Summers et al. (2003) further concluded that if PTCs were considered the "gold standard" for the TEN test, results obtained by both tests should be similar, if not identical. The results of this study found only a 56% agreement between the two methods. The authors concluded that their study did not support findings that the TEN test provides a sensitive and specific measure for identifying dead regions (Summers et al., 2003).

Summers et al. (2003) did acknowledge that the PTC measurements used in this study could have been influenced by irregular "beating" between the narrow-band noise masker employed in the study (100 Hz bandwidth) and the probe signal (pure-tone) when the narrow-band noise masker was presented slightly above or slightly below the pure-tone frequency under test. When this is the case, an additional cue can be provided to the listener indicating that the pure-tone is being presented (Moore & Alcantara, 2001) and some parts of the PTCs measured could be influenced by these cues. This could account for some of the disagreement found between the two measures. The detection of these “cues” could also contribute to the PTC measurement indicating no shifted tip (no dead region) when there really was a dead region. Although Summers et al. (2003) speculated on these possibilities, they stated in their discussion that they believed it was unlikely that PTCs would not identify a dead region (Summers et al., 2003).

Finally, the authors considered if utilizing different criteria for the identification of a dead region would influence the agreement between the two measures. By employing a more conservative criterion of 14 dB masked threshold on the TEN test to suggest a dead region, the agreement between the two measurements changed to 89%, indicating improved agreement on the two measurements for 16 of 18 ears (Summers et al., 2003). However, this is not the current recommended criterion for determining dead regions that either of the TEN tests (SPL or HL versions) suggest.

New Version of TEN (TEN (HL) test)

In response to some of the problems encountered with the first version of the TEN test, Moore et al. (2004) designed a new version of the test with measurements in dB HL. The first, or older, version of the test may be referred to as the TEN (SPL) and the new version the TEN (HL). The TEN (HL) is administered, and based, on the same rationale as the TEN (SPL) version; however the noise has been changed to produce almost equal masked thresholds in dB HL (for normal hearing listeners and listeners with sensorineural hearing loss but no dead regions). In this new version, the nominal level of the TEN noise (in dB HL/ERB$_N$) is now indicated by the level on the audiometer (in dB HL).

Therefore, a dial reading of 40 dB HL leads to a level/ERB$_N$ of 40 dB HL (Moore et al., 2004). The TEN (HL) also utilizes the same criteria for diagnosing a dead region.

One of the problems associated with the TEN (SPL) version of the test was that it was limited for evaluating listeners with severe or profound hearing losses because the TEN (recorded in dB SPL) was often perceived as too loud or uncomfortable for these patients to tolerate at the level needed to produce a 10 dB or more masked threshold. As a result, the new version uses a narrower bandwidth (354-6500 Hz) of the spectrally shaped noise. This bandwidth still allows the test to be used for the frequency range 500-4000 Hz, which is typically the frequency range of clinical importance, especially for the fitting of hearing aids. By reducing the bandwidth of the noise and making some other alterations to the noise, the overall level of the noise and its loudness are lower than the TEN (SPL) version. This allows for higher levels of the TEN (HL) to be utilized without causing as many loudness or tolerance issues (Moore et al., 2004).

A study was conducted to ensure that the new version of the TEN test still produced almost equal masked thresholds in dB HL for normally hearing and hearing-impaired listeners with no dead regions. Twelve participants (24 ears) with normal to near-normal hearing participated in the study (the range of normal to near-normal hearing was not defined in the study). The participants ranged in age from 26-58 years with a mean age of 42 years. Moore et al. (2004) only validated the test at the 60 dB HL TEN noise level, using a final step size of 2 dB to determine threshold. The authors did not provide a rationale for utilizing a 2 dB final step size (although this is standard in psychoacoustic measures); however, this is the final step size recommended by Moore et al. (2004) for measuring masked thresholds in the TEN (HL) noise. The results revealed little variation in mean masked thresholds measured across frequencies for all participants; all masked thresholds were close to 60 dB HL (as would be expected with individuals without dead regions when the TEN level was 60 dB HL). The minimum threshold measured in the TEN noise was 58 dB HL from 500 – 4000 Hz. The maximum threshold measured in the TEN noise was 62 dB HL at 750 Hz and from 1500 – 3000 Hz; the maximum threshold value was 64 dB HL at 500 and 1000 Hz. Finally, the maximum threshold value was 66 dB HL at 4000 Hz, with a standard deviation of 2.1 (Moore et al., 2004). The authors did note a 1.6 dB higher threshold level at 4000 Hz compared to the other frequencies. Although this difference was small, the authors accounted for the "1.6 dB boost" at 4000 Hz in the final version of the new TEN (HL) noise (Moore et al., 2004).

The authors tested this new, adjusted version of the test on 15 different participants (30 ears) with normal or near-normal hearing sensitivity (again normal or near-normal hearing was not defined in this study). The participants ranged in age from 23-54 with a mean age of 39 years. Again, the authors tested all participants at a level of 60 dB HL of TEN noise. The authors noted that all participants had masked thresholds close to 60 dB HL for the frequency range 500-4000 Hz on the adjusted version of the TEN as well. The minimum masked thresholds were 56 dB HL at 750 Hz and from 1500 – 4000 Hz; the minimum masked thresholds were 58 dB HL at 500 Hz and 1000 Hz. The maximum masked thresholds were 62 dB HL at 1500 Hz, 64 dB HL from 500 – 1000 Hz and 2000 – 3000 Hz. The maximum masked threshold at 4000 Hz was 66 dB HL, with a standard deviation of 2.7. The authors acknowledge that there does appear to be greater variability in masked thresholds at 4000 Hz; however, because the maximum masked threshold was not found to be greater than 66 dB HL (and therefore not causing a 10 dB or more shift indicative of a dead region), the authors concluded that the new version of the TEN (HL) was a valid measure for the detection of dead regions (Moore et al., 2004).

The authors did not elaborate on why they only tested the participants at 60 dB HL TEN noise, nor did they provide the rationale for only using one level of the TEN noise. In theory, the TEN test should produce masked thresholds that are close to the TEN noise level employed (regardless of level) for normal hearing listeners and listeners with hearing loss but no dead regions. In contrast, the original version of the TEN (SPL) was validated on normal hearing participants at three different levels of the TEN noise (30, 50, and 70 level dB SPL). However, the test developers did not determine if there was good agreement between the TEN test results obtained with either version and a more established measure (PTCs) for normal hearing individuals.

The TEN (HL) version has many advantages over the TEN (SPL) version. First, all measurements are conducted in dB HL which eliminates any confusion caused by converting from dB SPL to dB HL. Calibration of the test is less complicated because the test tone and noise were recorded in dB HL and now correspond to the dB HL value on the audiometer dial. Higher levels of the noise can be used to identify dead regions with this version of the test without causing distortion because the overall bandwidth of the noise has been reduced. It is recommended (Moore et al., 2004) that a single level of the TEN noise (dB HL/ERB_N) corresponding to a level that is at least 10 dB above the threshold measured in quiet in the frequency region of interest (i.e. where dead regions are expected) be employed. However, it is not a requirement to utilize the same TEN (HL) noise level for each test frequency. Different levels of the TEN noise can be administered at each frequency; however, the level of the TEN noise should be at least 10 dB above the threshold in quiet at the frequency under test (to ensure adequate masking). Finally, if only one level of the TEN (HL) is utilized across all seven test frequencies (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz) recorded on the compact disc (CD), the overall test time is approximately 5 minutes per ear according to the authors. Therefore, the TEN (HL) version is easier and less time consuming than the TEN (SPL) version (Moore et al., 2004).

Criteria and Prevalence of Dead Regions

The recommended criteria for the diagnosis of a dead region as identified by the TEN test vary across studies. In early studies (Baer, Moore, & Kluk, 2002; Mackersie et al., 2004; Moore et al., 2000; Vickers et al. 2001), and more recent studies using the new TEN (HL) test (Aazh & Moore, 2007; Vinay & Moore, 2007), a dead region is identified at a particular test frequency when the TEN noise produces a masked threshold that is 10 dB or higher (greater) than the absolute threshold measured in quiet at that frequency, and when the masked threshold is at least 10 dB or higher (greater) than the level of the TEN noise. This “rule,” or recommended criterion, was first suggested by Moore et al. (2000) when the authors validated the use of the TEN (SPL) test for identifying dead regions. In this study, all control participants demonstrated similar masked thresholds across test frequencies for three different TEN noise levels (30, 50, and 70 dB SPL). More specifically, the masked thresholds approximated the level of the TEN noise across frequencies, never varying from the level by more than 10 dB across frequencies. In contrast, some of the hearing- impaired participants in this study exhibited a significant threshold shift for some frequencies (those with dead regions). More specifically, the authors observed that for certain frequency regions, the tips of the PTCs were shifted, the masked thresholds were 10 dB or more higher than normal, and the TEN noise produced 10 dB or more of masking (meaning that the masked threshold was 10 dB higher than unmasked thresholds). These frequency regions were determined to represent dead regions (Moore et al., 2000).

Utilizing these same criteria for identifying a dead region, Vickers et al. (2001) found that out of 10 participants with high-frequency sensorineural hearing loss (48-76 years of age) seven participants had high-frequency dead regions and three did not (12 ears had dead regions, and 6 ears did not). To verify their findings on the TEN test, the investigators tested all participants using the same PTC measurements as described by Moore et al. (2000). The authors reported "good correspondence" between these two measures (Vickers et al., 2001). The authors did not provide any statistical analysis of these two measures; the correspondence relies on visually comparing the TEN test results with those of the PTCs. The authors noted that the participants with dead regions in this study also had more severe high-frequency hearing loss than participants who did not demonstrate dead regions (Vickers et al., 2001).

Another study by Vestergaard (2003) tested 22 participants with varying degrees of sloping and flat sensorineural hearing loss. The participants were required to have hearing losses greater than 60 dB HL at some frequencies to ensure that dead regions could be identified. Dead regions are not expected to be present in individuals with mild hearing losses. The participants ranged in age from 29-73 years, with a mean age of 60 years. All participants were tested on the TEN (SPL) test, and dead regions were identified by employing the same criteria as previously mentioned. Utilizing this "rule," this study identified 11 participants with dead regions and 11 with no dead regions (Vestergaard, 2003).

Preminger and her colleagues (2005) employed a stricter criterion for identifying a dead region when using the TEN (SPL) test. In this study, a dead region was considered present when the masked threshold was at least 15 dB above the threshold measured in quiet and 15 dB above the TEN noise level. The authors derived this criterion based on the better correspondence (89%) demonstrated by Summers et al. (2003) when their data were re-examined using a 14 dB shift criterion. Preminger et al. (2005) tested 49 participants with sensorineural hearing losses of 50-80 dB HL and varying hearing loss configurations. The participants ranged in age from 21-75 years with a mean age of 62.5 years. By employing this criterion in their study, Preminger et al. (2005) found that 14 (29%) of the participants had dead regions. It should be noted that no verification measure, such as the measurement of PTCs, was utilized in this study. Preminger et al. (2005) stated that based on previous studies (Moore et al., 2000; Summers et al., 2003) and when employing a stricter threshold shift criterion (14 dB or more) the TEN test results suggest the presence of dead regions (Preminger et al., 2005).

Vinay and Moore (2007) conducted a study to assess the prevalence of dead regions in a typical clinical population using the TEN (HL) test. Participants, ranging in age from 17 to 95 years (mean age 57 years) who demonstrated audiometric thresholds greater than 15 dB HL for at least one frequency (between 250 and 8000 Hz), with no air-bone gaps $\geq$ 10 dB and no middle ear pathologies were included in the study. The total number of participants was 308. The authors conducted the TEN test at 70 dB HL TEN noise for many of the participants. They reported utilizing a higher level, up to 85 dB HL

TEN noise, if the participant had audiometric thresholds corresponding to a severe or profound sensorineural hearing loss. The criteria suggested by Moore et al. (2001, 2004) for identifying a dead region was employed in this study (masked threshold 10 dB or more above the level of the TEN noise and the masked threshold was 10 dB or more above the absolute threshold indicated a dead region). The results showed that 177 (57.4%) participants had a dead region in one or both ears for at least one test frequency. The authors found no significant effect of gender nor age on the prevalence of dead regions; however, the percentage of ears identified with dead regions was higher for the oldest age group (71 to 95 years of age) compared to the three other age groups evaluated (17 through 30 years, 31 through 50 years, and 51 through 70 years of age) (Vinay & Moore, 2007). Again, it should be noted that the TEN test results were not compared or verified with any other measures (such as PTCs) in this study.

Aazh and Moore (2007) investigated the prevalence of dead regions in older adults (aged 63 to 101 years) with hearing loss. All participants had a sensorineural hearing loss of 60 to 85 dB HL at 4000 Hz (only 4000 Hz was assessed in this study). A total of 63 individuals (98 ears) participated in the study. The authors utilized the TEN (HL) test and employed the criteria suggested by Moore et al. (2001, 2004) for identifying dead regions. The results revealed that out of the 98 ears evaluated, 62 ears had no dead region and 36 ears were found to have a dead region at 4000 Hz (Aazh & Moore, 2007). This study only assessed the prevalence of dead regions at one test frequency (4000 Hz); the prevalence of dead regions at other frequencies for this older population was not assessed.

Age Effects

Moore (2004) states that the original TEN test (TEN SPL) criteria for diagnosing a dead region (mentioned above) were developed on a small sample of adults with moderate-to-severe sensorineural hearing loss. He further suggests that the criteria may not be appropriate for all participant populations. For example, Moore mentions that the criteria may not be appropriate for individuals with profound hearing loss or younger individuals (i.e., children and teenagers; Moore, 2004). He does not address whether different criteria may be needed for elderly individuals as well. The TEN (HL) version was validated on 15 individuals (30 ears) ranging in age from 23-54 years. This age range is not representative of all adults with hearing loss, and does not consider older normal-hearing adults.

One theory to explain why older listeners may have more difficulty than younger listeners on tasks requiring identification of a signal (tones, speech, etc.) in the presence of noise may be that they are less efficient listeners, or have reduced “detection efficiency” or “processing efficiency” (Aazh & Moore, 2007; Gifford & Bacon, 2005; Moore, Peters, & Glasberg, 1992; Patterson et al., 1982). For example, if a younger and older listener had the same auditory filters, but the older listener required the signal to be higher (above the level of the noise) at the output of the auditory filter in order to demonstrate similar performance as the younger listener, the older listener would be characterized as being less efficient. In this scenario, it is not the broadening of the auditory filter that is affecting performance, but the processing efficiency (which would involve more central cognitive functions rather than only peripheral function).

In order to parse out changes in frequency selectivity (tuning of the auditory system) and changes in processing efficiency that are independent of frequency selectivity, a notched noise masking paradigm (Patterson, 1976) can be employed to obtain auditory filter shapes (Patterson et al., 1982). Patterson et al. (1982), measured auditory filter shapes for three center frequencies (500, 2000, and 4000 Hz) using the notched noise masking paradigm. The signal (fixed in frequency) and masker (two broadband noise maskers) were presented simultaneously. Threshold for the signal frequency was measured as a function of the width of the notch in the noise. Both ears of 16 participants (aged 23 to 75 years) were tested (Patterson et al., 1982). The authors found that auditory filters broadened with increasing age for all center frequencies measured (500, 2000, and 4000 Hz). The researchers suggested that when considering an older (or even middle-aged) normal hearing listener's frequency selectivity ability, the broadening of auditory filters (one and a half times the width of young normal hearing listeners) associated with the aging process should be considered (Patterson et al., 1982).

While Patterson et al. (1982) found that older participants demonstrated wider auditory filter bandwidths for all signal frequencies tested, there are also many studies that have demonstrated that auditory filter bandwidths do not broaden with age (Peters & Hall, 1994; Sommers & Gehr, 1998; Sommers & Humes, 1993). In a more recent study, Gifford and Bacon (2005) conducted an experiment on auditory filter shapes of young and older matched normal hearing listeners to consider if age-related differences were observed. The "younger" participants in this study were aged 30 years or younger (mean age 25.6 years) and the "older" participants were aged 60 years or older (mean age 63.8 years). Based on the degree of education and the background of the participants selected for the study, the authors judged the older group to be "high functioning with respect to mental alertness and intellect" (Gifford & Bacon, 2005). The two groups were matched according to hearing sensitivity (within 5 dB) at 1200 Hz and 2400 Hz and either at 600 Hz or 4800 Hz (Gifford & Bacon, 2005).

As mentioned previously, "processing efficiency" or "detection efficiency" reflects an individual's ability to detect a signal in noise. This threshold value is calculated by subtracting the noise from the signal to determine the signal-to-noise ratio (Gifford & Bacon, 2005). In this study, the authors found that the signal-to-noise ratio at the output of the auditory filter (reflecting "processing efficiency") was approximately 9 dB higher for older hearing listeners compared to young listeners even though both groups were determined to have equivalent auditory filter bandwidths (Gifford & Bacon, 2005). The authors attributed the differences in performance observed between the two groups to be cognitively based because both groups had equivalent auditory filter bandwidths.

It has been demonstrated (Glasberg & Moore, 1986) that masked thresholds in broadband noise only differ by approximately 2-3 dB for normal hearing listeners and hearing-impaired listeners with no dead regions, with the hearing-impaired listeners demonstrating the 2-3 dB higher masked thresholds compared to normal hearing listeners (Glasberg & Moore, 1986). Therefore, for normal hearing listeners and listeners without dead regions, the signal can be at the same level of the noise and be detected (0 dB SNR) or the signal can be just slightly higher than the noise for detection (+2 to +3 dB SNR). The diagnosis of a dead region is determined when the signal needs to be 10 dB or higher above the broadband noise for detection. In a recent study by Aazh and Moore (2007), the SNRs for the non-dead region group varied from -5 dB to +9 dB. The authors suggested that the higher values, bordering on being close to having a dead region (+10 dB, therefore only differing by one dB), may be attributed to poorer "detection efficiency" (Patterson et al, 1982) in their participants. The authors point out that "detection efficiency" has been found to worsen with increasing age (Gifford & Bacon, 2005; Patterson et al., 1982; Peters & Moore, 1992). The participants in this study ranged in age from 63 to 101 years (Aazh & Moore, 2007).

One might speculate that if "detection efficiency" worsens with increasing age (Patterson et al., 1982; Peters & Moore, 1992), then all of the older participants in this study (who were 63 – 101 years) would be affected by decreased detection efficiency. Indeed, Aazh and Moore (2007) attribute the variability of SNRs demonstrated across participants in both the non-dead region group and the dead region group to the variability of "detection efficiency" across participants. For example, the authors found that 11 (31%) of ears diagnosed with a dead region only just qualified; meaning that the participants had SNRs of 10 or 11 dB (either just making the 10 dB SNR or 1 dB above the criteria). The authors further observed that 11 (18%) of the ears found not to have a dead region only just failed to meet the criteria; meaning participants had SNRs of 8 or 9 dB. Aazh and Moore (2007) offer that repeating the TEN (HL) test or administering a test that is independent of "detection efficiency" would be beneficial in these situations to assure that the participant either truly does or does not have a dead region (Aazh & Moore, 2007). This variability in processing efficiency observed for older listeners may have important implications when considering the criteria for a dead region.

In summary, the TEN (HL) version was validated on young adult listeners (aged 23-54), an age group which does not represent that of all adults with hearing loss and may not generalize to older listeners (Moore, et al., 2004). The recent study by Aazh and Moore (2007) demonstrated masked thresholds that varied a great deal more (-5 dB to +9 dB) in older hearing impaired listeners with no dead regions than was previously observed for normal hearing and hearing impaired listeners with no dead regions (2-3 dB variation) (Glasberg & Moore, 1986). Some studies have attributed these age differences to more cognitive factors, such as "detection efficiency" or "processing efficiency" (Aazh & Moore, 2007; Gifford & Bacon, 2005). Other studies (Patterson et al., 1982) have attributed these age-related differences not only to poorer detection efficiency, but also to physiological changes such as broadening of the auditory filters (Patterson et al., 1982). Because these differences on auditory measures between young and older listeners have been demonstrated, it is possible that current normative data for the TEN (HL) test, only validated on young to middle aged adult listeners may not be appropriate for the determination of cochlear dead regions in older adult listeners.

Chapter 3: Statement of Research Questions and Hypotheses

The overall objective of this study is to evaluate the effects of age on the TEN (HL) test, particularly for normal-hearing listeners. This study is designed to address the following questions:

1) Do older normal-hearing listeners show greater signal-to-noise ratios measured in the TEN (HL) noise than young normal-hearing listeners?
2) Is there an effect of TEN (HL) level on signal-to-noise ratios for both young and older normal-hearing listeners?
3) Is there an effect of test frequency on the signal-to-noise ratios for both young and older normal-hearing listeners?
4) Is there a test-retest effect on signal-to-noise ratios for both young and older normal-hearing listeners?
5) Is there a differential effect on signal-to-noise ratios for younger and older normal-hearing listeners that varies with TEN (HL) level, test frequency, and/or with trial (test-retest)?

Differences on auditory measures between young normal-hearing listeners and older normal- hearing listeners have been demonstrated throughout the literature (Dubno et al., 2002; Gifford & Bacon, 2005; Potash & Jones, 1977; Rees & Botwinick, 1971). The expected outcomes of this study are that older normal-hearing listeners will show greater masked threshold shifts in the TEN noise than younger normal-hearing listeners, demonstrated by poorer (higher) signal-to-noise ratios. Some research suggests that an individual's peripheral auditory filtering mechanism deteriorates with increasing age (Patterson et al., 1982). This may influence the older normal-hearing listeners' ability to detect signal frequencies as accurately as the younger normal-hearing listeners because it would be harder for them to separate the signal from the noise. Other research suggests that differences observed between younger and older listeners may be due to more central mechanisms such as poorer processing efficiency in the older listeners (Aazh & Moore, 2007; Gifford & Bacon, 2005; Moore et al., 1992; Moore et al., 2000).

It is hypothesized that poorer (higher) signal-to-noise ratios will be observed for the older normal hearing listeners compared to the younger normal hearing listeners when the most intense (80 dB HL) level of TEN noise is employed. The TEN (HL) test is designed to produce equal masked thresholds for individuals with normal hearing and individuals without dead regions regardless of the level of the TEN noise (Moore et al., 2004). However, it is hypothesized that the older group will show poorer (higher SNRs) in this study at the higher level of the TEN noise due to poorer processing efficiency (Gifford & Bacon, 2005; Patterson et al., 1982) and/or due to over-masking (Boettcher, 2002).

There should be no effect of frequency observed in this study. The TEN (HL) test was designed to produce equal masked thresholds across test frequency for normal hearing listeners and individuals with no dead regions (Moore et al., 2004). Previous studies have found no differences in SNRs for normal hearing listeners across test frequencies for the TEN test (Moore et al., 2000; Moore et al., 2004). It is further hypothesized that if the TEN (HL) is a valid and reliable test, no difference in performance would be expected from one test session to the next session for either group of participants. Previous studies have found the TEN test to have good repeatability (Cairns et al., 2007; Munro et al., 2005).

The TEN (HL) test was validated on 15 normal to near-normal hearing listeners aged 23-54, with a mean age of 39 years (Moore et al., 2004). Also, the TEN (HL) test was validated only utilizing one level of TEN noise (60 dB HL TEN noise) across all test frequencies. If age-related differences in thresholds measured in the TEN noise are observed in the proposed investigation, then it is possible that new age-appropriate normative data may be needed for the determination of dead regions in older adult listeners.

Chapter 4: Method

Participants

A total of 36 individuals, ranging in age from 18 to 38 years and 61 to 81 years, were recruited for this study. All participants were recruited from flyers (see Appendix C) at the University of Maryland College Park Speech and Hearing Clinic and the University of Maryland Medical Center in Baltimore, MD, and from website postings on the Hearing and Speech Sciences (HESP) website (see Appendix D). Participants were also recruited by word of mouth, recruited from classes at the University of Maryland College Park, and recruited by asking participants from prior studies if they would like to participate in this study. All participants had normal cognitive awareness as demonstrated by scores in the normal range (0-2) on the Short Portable Mental Status Questionnaire (Pfieffer, 1975), and reported no known hearing loss, history of middle ear pathology or surgery, and no sound tolerance problems (hyperacusis). No restrictions were placed on gender, race, ethnic origin, socioeconomic level, or religion for the purposes of this study. All participants were native speakers of American English.

All participants demonstrated normal to near-normal hearing sensitivity. Normal to near-normal hearing sensitivity was defined in this study as pure-tone air and bone conduction thresholds $\leq$ 30 dB HL for the frequency region 250-8000 Hz with no air-bone gaps (>10 dB). These criteria were selected to eliminate significant hearing loss as a source of variability and to determine normal performance on the TEN (HL) test. Although audiometric thresholds of 16 to 30 dB HL are clinically classified as slight-to-mild hearing losses, for the purposes of this study these ranges can be included as near-normal hearing, because they are not indicative of cochlear dead regions. Cochlear dead regions are typically associated with moderately-severe to profound hearing loss. It would be expected that individuals with slight-to-mild sensorineural hearing loss would perform the same on the TEN test as normally hearing individuals (Moore, 2004). For these individuals, the inner hair cells are still functioning appropriately (as mentioned previously, IHC damage and/or loss is associated with hearing losses of 55 to 60 dB HL or greater) (Liberman & Dodds, 1984; Ruggero et al., 1997; Yates, 1990). For individuals determined to have cochlear dead regions, the inner hair cells in these regions are too damaged or destroyed to be functioning appropriately.

On the basis of these criteria, participants were assigned to one of two groups depending on the participant's age. This resulted in a control group (n = 18) consisting of female and male participants that ranged in age from 21 to 34 years of age (M = 25.11 years of age). The experimental group (n = 18) consisted of female and male participants that ranged in age from 61 to 76 years of age (M = 66.66 years of age). Table 1 and Table 2 display descriptive factors of both groups (gender, age, ear tested) and the specific air-conduction pure-tone thresholds measured using a standard clinical technique (explained below). Figure 1 illustrates the mean pure-tone air conduction thresholds of both groups at seven audiometric frequencies (250, 500, 1000, 2000, 4000, and 8000 Hz).

Preliminary Clinical Measures

All participants completed a case history questionnaire (see Appendix A) and the Short Portable Mental Status Questionnaire (see Appendix B) (Pfeiffer, 1975). These two questionnaires were administered to the participants orally by the investigator and answers were recorded on the respective data sheets. All participants were administered a diagnostic hearing evaluation consisting of pure-tone air and bone conduction

Table 1

Descriptive characteristics for the younger normal hearing group (gender, age, ear tested) and pure-tone audiometric thresholds for the ear tested.

Participant #	Gender	Age	Ear	250	500	1000	2000	4000	8000
1	F	27	R	10	10	5	5	0	5
2	F	25	L	5	5	5	5	-5	5
3	F	23	L	10	10	5	10	5	10
4	F	23	R	5	10	5	5	5	5
5	F	25	R	0	0	-5	-5	0	5
6	M	27	L	5	5	5	5	0	15
7	M	28	R	15	20	20	5	10	0
8	F	27	L	10	0	0	0	-5	0
9	F	34	L	0	0	5	0	0	10
10	F	25	R	10	5	0	0	5	10
11	F	25	R	15	20	15	5	0	5
12	M	25	L	0	5	0	0	-5	10
13	M	23	R	10	5	0	10	0	5
14	F	25	R	10	20	10	5	5	0
15	F	23	L	10	10	5	0	0	5
16	F	24	R	10	5	0	5	0	0
17	F	22	L	5	5	0	0	0	0
18	F	21	R	5	5	0	0	10	5

Table 2

Descriptive characteristics for the older normal hearing group (gender, age, ear tested) and pure-tone audiometric thresholds for the ear tested.

Participant #	Gender	Age	Ear	250	500	1000	2000	4000	8000
19	F	66	L	5	0	5	5	10	15
20	F	61	R	5	10	10	15	5	20
21	F	66	R	15	10	5	0	15	25
22	F	62	L	15	15	10	20	10	15
23	F	72	L	5	10	15	10	10	20
24	F	63	R	10	15	25	20	5	15
25	M	67	L	10	10	15	15	20	30
26	M	71	L	0	5	5	15	5	0
27	F	69	R	25	25	10	10	15	30
28	F	69	L	15	15	10	10	10	20
29	F	76	R	0	5	15	15	25	30
30	M	67	R	10	10	5	0	20	20
31	F	64	R	10	10	15	5	30	30
32	F	64	L	10	15	15	10	10	15
33	M	62	R	10	25	25	25	25	30
34	F	75	R	15	20	15	20	10	25
35	F	61	L	5	5	10	10	0	25
36	F	65	L	0	15	10	10	10	20

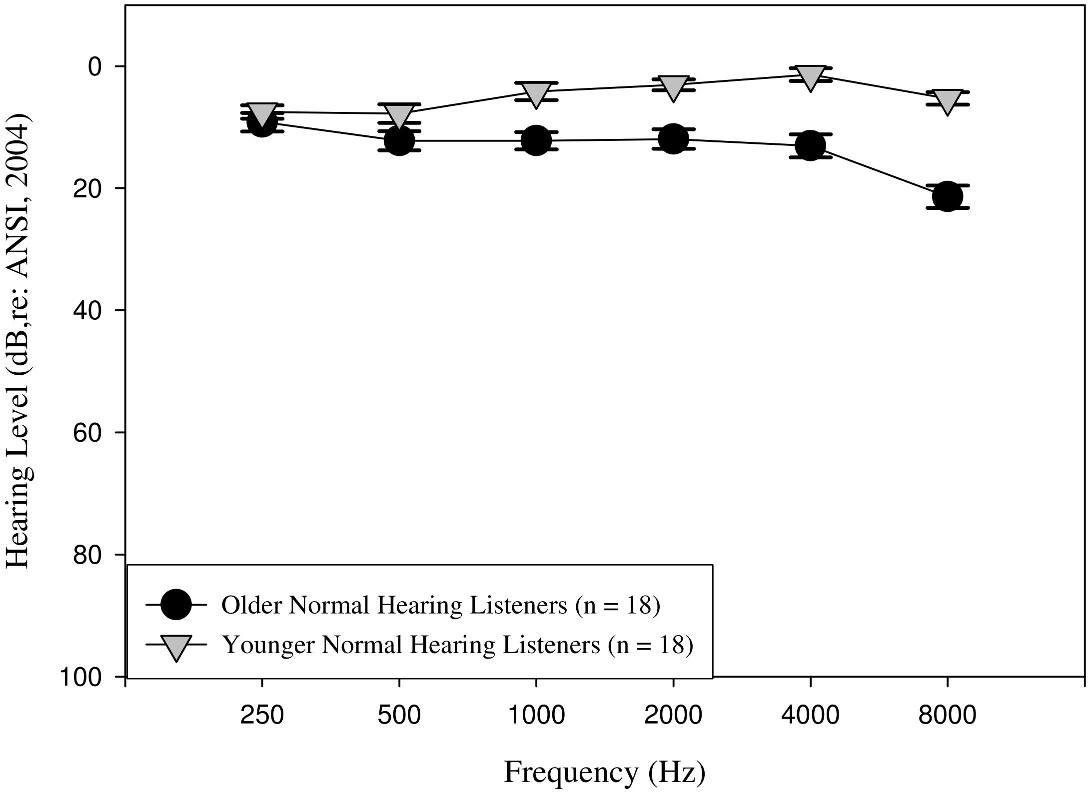

Figure 2. Mean pure-tone air conduction thresholds in test ear for younger and older listeners at audiometric frequencies using a standard clinical technique. Error bars indicate the standard error of the mean.

audiometric testing to determine if they met the criteria for participation in the study. Audiometric testing was conducted in a sound-treated test booth using a Grason-Stadler (GSI-61) audiometer calibrated to American National Standards Institute (ANSI) standards S3.6-2004 (ANSI, 2004). Pure-tone air conduction (AC) thresholds were measured using insert earphones (Ear Tone ER-3A) in both ears at the octave intervals 250, 500, 1000, 2000, 4000, and 8000 Hz. Pure-tone bone-conduction (BC) thresholds were measured at 500, 1000, 2000, and 4000 Hz. The participants were asked to press a response button every time they thought they heard a beep or tone.

A speech recognition threshold (SRT) was determined for both ears using spondee words via monitored live voice (MLV). The participants were informed that they would hear the investigator say some two syllable words, like “hotdog” or “baseball.” These words were initially presented at a suprathreshold level, with the level decreasing following a correct response. The participants were asked to repeat back whatever word they perceived the investigator said. A bracketing procedure was employed until the lowest level (in dB HL) at which the participant correctly repeated back three responses was identified; this was taken as the SRT. The SRT was compared to the three frequency pure-tone average (500, 1000, 2000 Hz) to verify audiometric results.

Word recognition testing utilizing a monosyllabic word test (Northwestern University Test #6, or NU-6) was administered at a suprathreshold level via monitored live voice. The participants were informed that they would hear the investigator say some words to them in one ear and hear a constant noise, like running water or static, in their opposite ear. The participants were asked to ignore the noise and repeat back whatever word they perceived the investigator said; guessing was encouraged. The percentage of words that the participant repeated correctly out of the total list of words represented their word recognition scores. This measure was administered to both ears.

Acoustic immittance measures (using a 226 Hz probe tone) were assessed using an acoustic immittance unit (e.g., GSI Tymp Star) in order to assure that participants had no middle ear pathology. These measures consisted of tympanometry and acoustic reflex threshold assessment (ipsilateral and contralateral). Tympanometric results were considered normal if the static admittance value was 0.3 mmhos or greater (Margolis & Goycoolea, 1993) and if the middle ear pressure was between -100 and +100 daPa. Contralateral acoustic reflexes were considered normal if they were elicited at levels that were equal to or less than the 90th percentile criterion established by Silman and Gelfand (1981) for individuals with normal hearing or cochlear hearing loss (Silman & Gelfand, 1981). Some individuals in both groups demonstrated slightly higher contralateral acoustic reflex thresholds than the 90th percentile criterion (+5 dB), particularly at 500 Hz. These participants demonstrated normal tympanometry, no air-bone gaps, and normal pure-tone thresholds for all test frequencies. Therefore, it was determined that these participants demonstrated normal to near-normal hearing sensitivity. On the basis of these test results, adults aged 18 to 38 and aged 61 to 81 determined to have normal to near-normal hearing sensitivity qualified for this study.

Stimuli and Equipment

The TEN (HL) test consists of compact disc (CD) recordings of a special type of spectrally-shaped noise referred to as “threshold-equalizing noise” (Moore et al., 2000; Moore et al., 2003; Moore et al., 2004) and recordings of seven pure-tone signals (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz). The TEN noise has been shaped to provide equal masked thresholds (in dB HL) for normal hearing listeners and individuals without dead regions across the frequency range 500-4000 Hz.

The test is designed to be used with a two-channel audiometer and consists of eight total recorded tracks. The TEN (HL) noise is recorded on channel two (or the left channel) of tracks two through eight. Pure-tone signals, ranging in frequency from 500 to 4000 Hz are recorded on channel one (or the right channel) of tracks two through eight, respectively. A calibration tone is recorded on both channels of Track 1. In this study, the CD was played on a CD player that was routed to a Grason-Stadler (GSI-61) audiometer. All test signals were delivered to the participants through insert earphones (Ear Tone ER-3A) in a sound-treated booth.

Calibration

The GSI audiometer was calibrated according to American National Standards Institute (ANSI) standards S3.6-2004 (ANSI, 2004). Calibration of the test tones was conducted prior to testing of each participant by following the calibration method that is recommended for the TEN (HL) test (Moore et al., 2003). The left output from the CD player was routed to channel one (or channel A) on the audiometer and the right output was routed to channel two (or channel B). While playing Track 1 on the CD continuously, the VU meters of both channels were adjusted to read 0 dB for both channels.

The output SPL from the earphone was checked with a sound level meter and a $2cm^3$ coupler. Specifically, the SPL measured when the pure-tone test signal is played from the CD and adjusted to 0 VU should correspond to the Reference Equivalent

Threshold SPL (RETSPL) for the signal (ANSI, 2004). Additionally, the output SPL of the TEN noise was calibrated with the sound level meter and the 2 cm^3 coupler. The overall level of the TEN (HL) noise measured in the coupler in dB SPL was found to be approximately 22 dB higher than the nominal value of the TEN (HL) noise masker (Moore et al., 2004). Therefore, the output SPL was expected to correspond to the nominal value of each TEN noise masker plus approximately 22 dB. Calibration of the TEN masker at 60 dB HL and 80 dB HL indicated that the overall level of the TEN (HL) noise is approximately 17 dB higher measured in dB SPL (i.e., the 60 dB TEN noise produced 77.3 dB SPL in the coupler). Calibration was performed on a weekly basis.

Procedures

The experimental measure, the TEN (HL) test, was conducted in the sound-treated booth after the preliminary measures confirmed that the participants qualified for this experiment and agreed to participate in the study. Measurements were conducted for one ear, using the ear with better pure-tone thresholds for the test frequencies 500-4000 Hz because these are the pure-tone frequencies recorded on the TEN (HL) CD and represent the frequencies most often evaluated clinically. If there was no difference between the hearing sensitivity in both ears, the test ear was selected by counter-balancing between left and right ears in an attempt to have an equal number of right and left ears. This resulted in 9 right ears and 9 left ears tested for the older normal hearing group and 10 right ears and 8 left ears for the younger hearing group (see Table 1).

To determine each participant's threshold in quiet, absolute audiometric thresholds were measured using the test tones recorded on the TEN (HL) CD for the test frequencies 500, 750, 1000, 1500, 2000, 3000, and 4000 Hz using tracks 2-8 respectively.

The presentation order of the test tones (frequencies) was randomized for each participant and recorded on a data sheet. The presentation level of all pure-tones in quiet started at 40 dB HL at each frequency. All test tones were presented using the standardized modified Hughson-Westlake technique described by Carhart and Jerger (1959) to determine the absolute threshold at each frequency, with a final step size of 2-dB. The duration of each test tone was approximately 1-2 seconds.

All participants were asked to detect these same test tones in the presence of a continuous noise that was presented in the same ear as the signal frequency. The noise is called "threshold-equalizing noise" (TEN) and is designed to produce equal masked thresholds (in dB HL) for the above-mentioned test frequencies for normal-hearing listeners and individuals with no dead regions (Moore et al., 2004). The TEN noise was presented continuously at each frequency for the amount of time needed to determine threshold at each frequency (approximately 1-2 minutes). Three presentation levels of the noise were presented in separate conditions: 40 dB HL, 60 dB HL, and 80 dB HL representing a low level, medium level, and loud level of the TEN noise respectively.

The presentation order of the pure-tone thresholds recorded on the TEN (HL) CD in quiet and the different TEN (HL) levels was randomized, as well as the different test frequencies, to control for learning effects. To consider test-retest reliability, all conditions were conducted twice. Therefore, the four conditions (pure-tone thresholds in quiet using the TEN (HL) CD and three TEN noise levels) were randomized and the different test frequencies in each condition were randomized as well. Then the participants took a brief break (ranging from 5-10 minutes) where they were allowed to move around, get a drink of water, etc. After the break, the second run ensued. Again, all four conditions were presented in randomized order and the different test frequencies in each condition were presented in randomized order as well.

For the three TEN (HL) levels, all pure tones were presented initially at 10 dB above the presentation level of the noise employed at each test frequency as a uniform starting point in determining threshold in the presence of the TEN noise. For example, at 40 dB HL the TEN noise was presented at 40 dB HL and the pure-tone signal was initially presented simultaneously at 50 dB HL. All participants were given a response button and asked to press the button every time they heard the "beep" or "tone" for the measurement of the test frequencies in quiet. For the measurements in noise, the participants were informed that they would hear a constant "noise" being played and a "tone" or "beep" similar to the one they heard previously presented (in quiet) to their test ear. They were asked to concentrate on the "tone" or "beep," while ignoring the noise, and press the button every time they heard the "tone" or "beep." All test tones were presented using the modified Hughson-Westlake standardized technique described by Carhart and Jerger (1959). As recommended by Moore et al. (2004), a 2-dB final step size was employed to determine absolute threshold in both quiet and in the noise condition. More specifically, the initial presentation of the test tone was 10 dB above the level of the TEN noise (fixed in level). If the participant responded correctly, the presentation level of the pure-tone was decreased by 10 dB until there was no response. Upon no response, the presentation level of the pure-tone was increased by 5 dB until there was a correct response. After the next correct response, the presentation level of the pure-tone was decreased by 10 dB until there was no response. Then the presentation level of the pure-tone was altered using ascending and descending step sizes of 2 dB until the participant responded correctly on two successive ascending trials. This response was taken as the threshold at that test frequency and recorded on the data sheet.

This project was approved by the Institutional Review Board for Human Subjects Research at the University of Maryland on February 5, 2007. A copy of all consent forms and questionnaires can be found in the appendices.

Statistical Analysis

Thresholds measured in three different levels of the TEN noise (40 dB HL, 60 dB HL, and 80 dB HL) were collected at seven test frequencies (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz) on two different trials for 18 young normal hearing listeners and 18 older normal hearing listeners. Thresholds in quiet using the TEN (HL) CD were also measured for both groups at the same frequencies on two different trials. The actual threshold shift (due to masking noise) at each test frequency for each level of the TEN noise was calculated by subtracting the threshold measured in the TEN noise from the level of the TEN noise, thus representing the signal-to-noise ratio (SNR) at each test frequency. For example, when the TEN noise is presented at 40 dB HL at 500 Hz, if the threshold recorded was 45 dB HL, the SNR at 500 Hz would be +5 dB SNR. The dependent variable was the amount of threshold shift measured in the TEN noise, or the SNR value. The independent variables were age group (young normal hearing listeners versus older normal hearing listeners), level of the TEN noise (40 dB HL, 60 dB HL, and 80 dB HL), frequency (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz) and trial (two trials total). A mixed analysis of variance (ANOVA) was conducted to analyze the main effects of age group, level of the TEN noise, frequency, and trial and the interaction between these four variables. The design employed was a 2x3x7x2 multifactorial design, with one between-subjects factor (the two age groups) and three within-subjects factors (the three levels of the TEN noise, the seven test frequencies, and the two trials). Significant findings reflect an alpha level of $p < .01$. The Statistical Package for Social Sciences Software (SPSS) 11.0 for Windows Student Version and SPSS 13.0 was used for data analysis.

Chapter 5: Results

Signal-to-Noise Ratios (SNRs)

As a first step to data analysis, the mean SNRs for both groups were calculated for each of seven test frequencies (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz) at the three TEN noise levels (40 dB HL, 60 dB HL, and 80 dB HL) for two trials. The individual listeners' SNR data subsequently were analyzed using a mixed analysis of variance (ANOVA) with three within-subjects factors (TEN noise level, frequency, and trial) and one between-subjects factor (group). Some of the ANOVA results violated Mauchley's Test for Sphericity. Consequently, the Greenhouse-Geisser correction was applied in these instances for the degrees of freedom. Results of the main ANOVA are shown in Table 3. As the table indicates, the analysis revealed significant main effects (all at a significance level of $p < .01$) of TEN noise level, trial, frequency, and group and significant two-way interactions between TEN noise level and group, frequency and group, and TEN noise level and frequency. The main effect of trial was not observed in any interaction. This main effect indicates that all participants performed better (lower SNR) on trial two (M = -2.0556, SE = 0.13) compared to trial one (M = -1.6905, SE = 0.14). The effect of trial is illustrated in Figure 2.

Post-hoc testing for the interaction of group and TEN noise level [F(1.7,58.3) = 6.891, $p < .01$] was conducted to determine the effect of group for each of the three TEN noise levels (40 dB HL, 60 dB HL, and 80 dB HL) and the effect of the three TEN noise levels for each group. Figure 3 illustrates the mean SNRs calculated for both groups at the three TEN noise levels. The figure shows that the younger group consistently performed better (lower SNRs) than the older group at all three TEN noise levels.

Table 3

Summary of mixed analysis of variance (ANOVA) results

Variables	*F*	*df*	*p*-value
Main Effects			
Level	158.243	1.7, 58.3	0.000*
Trial	7.717	1, 34	0.009*
Frequency	27.466	4.4, 204	0.000*
Group	40.588	1, 34	0.000*
Two-way Interactions			
Level * Group	6.891	1.7, 58.3	0.003*
Trial * Group	0.582	1, 34	0.451
Frequency * Group	3.229	6, 204	0.005*
Level * Trial	0.516	2, 68	0.599
Level * Frequency	6.106	7.7, 261.8	0.000*
Trial * Frequency	2.048	6, 204	0.061
Three-way Interactions			
Level * Trial * Group	0.183	2, 68	0.833
Level * Frequency * Group	1.822	12, 408	0.076
Trial * Frequency * Group	2.147	6, 204	0.065
Level * Trial * Frequency	0.821	12, 408	0.629
Four-way Interaction			
Level * Trial * Frequency * Group	1.303	12, 40	0.214

*$p < .01$

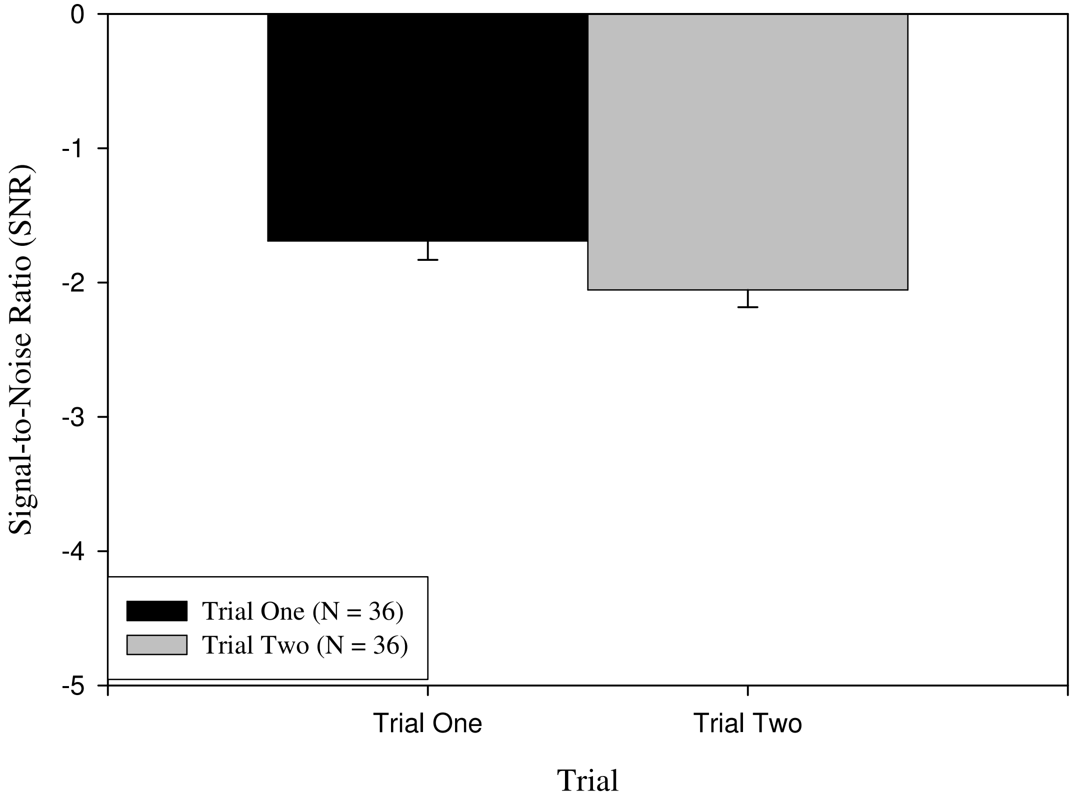

Figure 3. Mean SNRs of both groups for trial one and trial two. Error bars indicate the standard error of the mean.

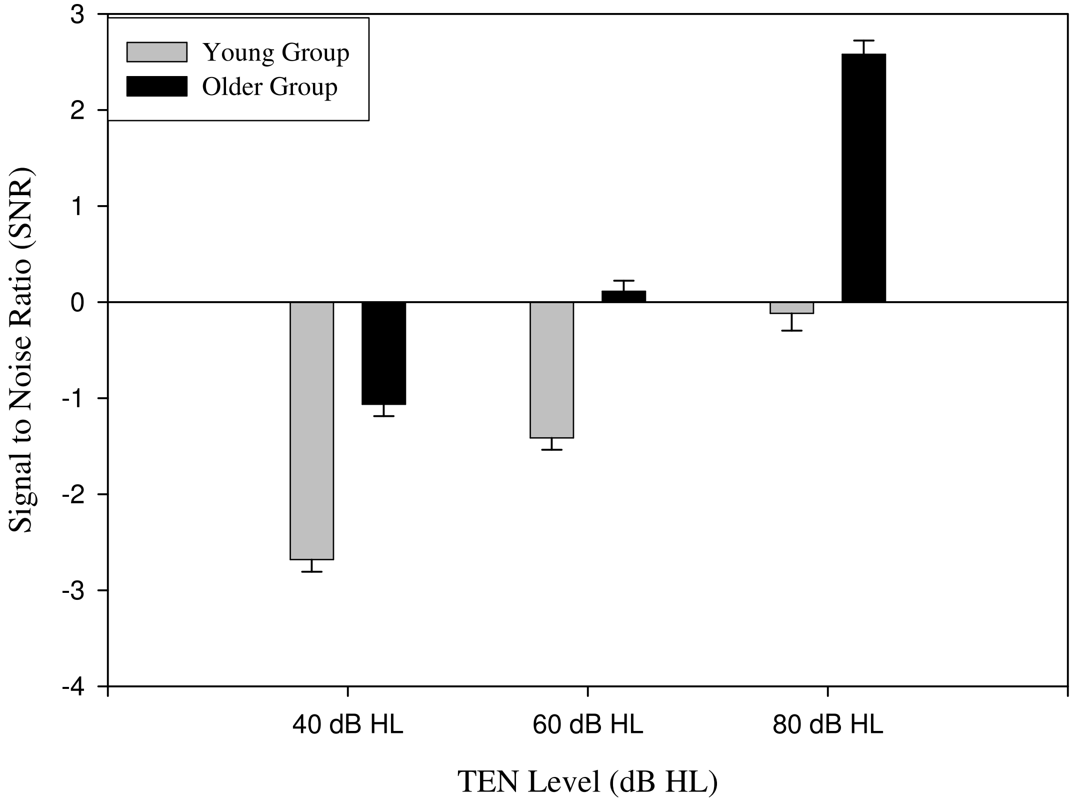

Figure 4. Mean SNRs for the younger and older normal hearing groups (n = 18/group) at three TEN noise levels. Error bars indicate the standard error of the mean.

Table 4

T-test results of the group effect at each TEN noise level

TEN noise level	*t*	*df*	*p*-value
40 dB HL	-9.166	502	0.000*
60 dB HL	-9.161	502	0.000*
80 dB HL	-11.807	502	0.000*

*$p < .003$.

Examination of the figure also suggests that the greatest difference in SNRs between the two groups is at the highest level of TEN noise (80 dB HL). Results of pairwise comparisons, shown in Table 4, indicate a significant difference ($p < .003$; adjusted with Bonferroni correction) in SNR between groups at each of the three TEN noise levels. Simple main effects analyses were conducted to examine the significance of TEN noise level for each group, and revealed a significant effect of TEN noise level for both the younger group [$F(2,753) = 77.858$, $p < .01$] and the older group [$F(2,750) = 216.723$, $p < .01$]. Multiple comparisons tests, utilizing Scheffe post-hoc testing, were conducted to determine the significance of differences between each TEN noise level, separately for each group. Table 5 shows these comparisons for the younger group and Table 6 shows these comparisons for the older group. As both tables indicate, a significant difference was found between each pair of TEN noise levels for both groups.

Examination of the paired comparison results indicates that a possible source of the interaction effect was the magnitude of the differences in SNRs measured at the 80 dB HL TEN noise level ($t = -11.807$) versus the two lower levels of TEN noise at 40 dB HL ($t = -9.166$) and at 60 dB HL ($t = -9.161$). Therefore, while the difference between the two groups was significant at the 40 dB HL TEN noise level and the 60 dB HL TEN noise level, this difference is greatest at the 80 dB HL TEN noise level. A similar examination of the simple main effects results also indicate that a possible source of the interaction effect was the magnitude of the differences in SNRs between the younger normal hearing group [$F(2,753) = 77.858$, $p <.01$] and the older normal hearing group [$F(2,750) = 216.723$, $p < .01$]. Again, there was a significant effect of TEN noise level for each group, but the magnitude of this effect appears to be greater for the older group

Table 5

Results of multiple comparisons of TEN noise levels using Scheffe post-hoc testing for the younger group

(I) TEN noise level	(J) TEN noise level	Mean Difference (I-J)	*p*-value
40 dB HL	60 dB HL	-1.26984	0.000*
	80 dB HL	-2.56349	0.000*
60 dB HL	40 dB HL	1.26984	0.000*
	80 dB HL	-1.29365	0.000*
80 dB HL	40 dB HL	2.56349	0.000*
	60 dB HL	1.29365	0.000*

*$p < .01$.

Table 6

Results of multiple comparisons of TEN noise levels using Scheffe post-hoc testing for the older group

(I) TEN noise level	(J) TEN noise level	Mean Difference (I-J)	*p*-value
40 dB HL	60 dB HL	-1.17131	0.000*
	80 dB HL	-3.64940	0.000*
60 dB HL	40 dB HL	1.17131	0.000*
	80 dB HL	-2.47809	0.000*
80 dB HL	40 dB HL	3.64940	0.000*
	60 dB HL	2.47809	0.000*

*$p < .01$.

as suggested by the much larger *F*-value.

Post-hoc testing for the interaction of group and frequency [F(6,204) = 3.229, *p* < .01] was conducted to determine the effect of group for each of the seven test frequencies (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz) and the effect of frequency for each group. The mean SNRs for both the younger and older groups (collapsed across TEN level) at each test frequency are illustrated in Figure 4. The figure shows that the younger group performed better (lower SNRs) at each frequency compared to the older group. The figure suggests that the greatest difference in SNR between the two groups is at the lowest and highest test frequencies (500 and 4000 Hz respectively). Pairwise comparisons of group and frequency revealed there was a significant difference between the SNRs of the younger and older groups at each of the seven test frequencies. These results can be found in Table 7. The Bonferroni correction for multiple *t*-tests was applied.

A simple main effects analysis was conducted to evaluate the effect of frequency for the younger group and the older group. A significant effect of frequency was found for the younger group [F(6,749) = 17.974, *p* < .01] and the older group [F(6,746) = 6.889, *p* < .01]. Consequently, multiple comparison tests (Scheffe) were conducted to determine the significance of the differences in SNR between each pair of test frequencies. Results for the younger group are shown in Table 8. As can be seen from the table, the results revealed a significant difference between the SNR measured at 4000 Hz and the SNR obtained at all other frequencies with the exception of 500 Hz. A significant difference was also found between the SNRs measured at 500 Hz and 750 Hz and between 500 Hz and 1500 Hz. Therefore, for the younger group, the differences between SNR across

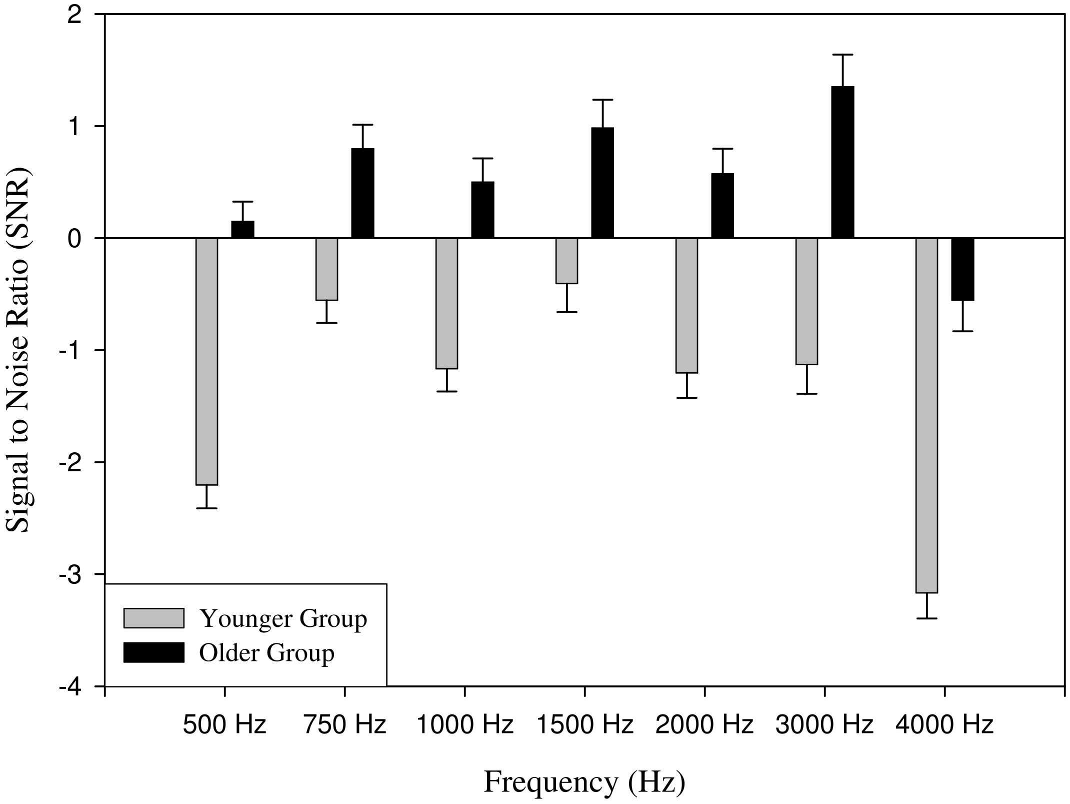

Figure 5. Mean SNRs for the younger group and the older groups (n = 18/group) at seven test frequencies. Error bars indicate the standard error of the mean.

Table 7

Results of independent samples t-tests between the younger and older groups at each of seven test frequencies

Frequency	*t*	*df*	*p*-value
500 Hz	-8.615	214	0.000*
750 Hz	-4.581	214	0.000*
1000 Hz	-5.706	214	0.000*
1500 Hz	-3.797	214	0.000*
2000 Hz	-5.650	214	0.000*
3000 Hz	-6.461	214	0.000*
4000 Hz	-7.258	214	0.000*

*$p < .001$

Table 8

Results of multiple comparisons using Scheffe post-hoc testing for the younger group at each frequency

(I) Frequency	(J) Frequency	Mean Difference (I-J)	*p*-value
500 Hz	750 Hz	-1.64815	0.000*
	1000 Hz	-1.03704	0.114
	1500 Hz	-1.79630	0.000*
	2000 Hz	-1.00000	0.145
	3000 Hz	-1.07407	0.089
	4000 Hz	0.96296	0.182
750 Hz	500 Hz	1.64815	0.000*
	1000 Hz	0.61111	0.734
	1500 Hz	-.14815	1.000
	2000 Hz	0.64815	0.674
	3000 Hz	0.57407	0.789
	4000 Hz	2.61111	0.000*
1000 Hz	500 Hz	1.03704	0.114
	750 Hz	-0.61111	0.734
	1500 Hz	-0.75926	0.480
	2000 Hz	0.03704	1.000
	3000 Hz	-0.03704	1.000
	4000 Hz	2.0000	0.000*
1500 Hz	500 Hz	1.79630	0.000*
	750 Hz	0.14815	1.000

	1000 Hz	0.75926	0.480
	2000 Hz	0.79630	0.416
	3000 Hz	0.72222	0.545
	4000 Hz	2.75926	0.000*
2000 Hz	500 Hz	1.00000	0.145
	750 Hz	-0.64815	0.674
	1000 Hz	-0.03704	1.000
	1500 Hz	-0.79630	0.416
	3000 Hz	-0.07407	1.000
	4000 Hz	1.96296	0.000*
3000 Hz	500 Hz	1.07407	0.089
	750 Hz	-0.57407	0.789
	1000 Hz	0.03704	1.000
	1500 Hz	-0.72222	0.545
	2000 Hz	0.07407	1.000
	4000 Hz	2.03704	0.000*
4000 Hz	500 Hz	-0.96296	0.182
	750 Hz	-2.61111	0.000*
	1000 Hz	-2.00000	0.000*
	1500 Hz	-2.75926	0.000*
	2000 Hz	-1.96296	0.000*
	3000 Hz	-2.03704	0.000*

*$p < .01$.

Table 9

Results of multiple comparisons using Scheffe post-hoc testing for the older group at each frequency

(I) Frequency	(J) Frequency	Mean Difference (I-J)	*p*-value
500 Hz	750 Hz	-0.64815	0.710
	1000 Hz	-0.35185	0.981
	1500 Hz	-0.88042	0.338
	2000 Hz	-0.42593	0.951
	3000 Hz	-1.20370	0.045
	4000 Hz	0.70370	0.620
750 Hz	500 Hz	0.64815	0.710
	1000 Hz	0.29630	0.992
	1500 Hz	-0.23228	0.998
	2000 Hz	0.22222	0.998
	3000 Hz	-0.55556	0.838
	4000 Hz	1.35185	0.013
1000 Hz	500 Hz	0.35185	0.981
	750 Hz	-0.29630	0.992
	1500 Hz	-0.52857	0.873
	2000 Hz	-0.07407	1.000
	3000 Hz	-0.85185	0.372
	4000 Hz	1.05556	0.128
1500 Hz	500 Hz	0.88042	0.338

	750 Hz	0.23228	0.998
	1000 Hz	0.52857	0.873
	2000 Hz	0.45450	0.935
	3000 Hz	-0.32328	0.988
	4000 Hz	1.58413	0.001*
2000 Hz	500 Hz	0.42583	0.951
	750 Hz	-0.22222	0.998
	1000 Hz	0.07407	1.000
	1500 Hz	-0.45450	0.935
	3000 Hz	-0.77778	0.494
	4000 Hz	1.12963	0.078
3000 Hz	500 Hz	1.20370	0.045
	750 Hz	0.55556	0.838
	1000 Hz	0.85185	0.372
	1500 Hz	0.32328	0.988
	2000 Hz	0.77778	0.494
	4000 Hz	1.90741	0.000*
4000 Hz	500 Hz	-0.70370	0.620
	750 Hz	-1.35185	0.013
	1000 Hz	-1.05556	0.128
	1500 Hz	-1.58413	0.001*
	2000 Hz	-1.12963	0.078
	3000 Hz	-1.90741	0.000*

frequency appear to be significant at the lower frequencies (500 Hz vs. 750 Hz and 1500 Hz) and at the highest test frequency (4000 Hz vs. 750, 1000, 1500, 2000, and 3000 Hz).

Results of Sheffe contrast tests can be found in Table 9 for the older group. As the table indicates, a significant difference was found between SNRs measured at 4000 Hz versus 750, 1500, and 3000 Hz. These results suggest the older group performed differently at the highest test frequency (4000 Hz) compared to two other test frequencies (750 and 1500 Hz). Thus, the specific frequency effect was somewhat different between the two groups.

Post-hoc testing for the interaction between TEN noise level and frequency [F(7.7, 261.8) = 6.106, $p < .01$] was conducted to determine the effect of TEN noise level for each of the seven test frequencies and the effect of frequency for each of the three TEN noise levels. The mean SNRs for the three TEN noise levels for all participants measured at each of the seven test frequencies are displayed in Figure 5. In Figure 5 there is a clear trend of all participants having higher (poorer SNRs) when listening in the 80 dB HL TEN noise compared to the two lower levels of TEN noise (40 and 60 dB HL) at all of the test frequencies. It is also apparent that all SNRs at each TEN noise level tend to be lower at the highest and lowest test frequency, compared to SNRs in the mid frequencies.

Simple main effects analyses revealed a significant effect of frequency at the 40 dB HL TEN noise level [F(6,497) = 14.219, $p < .01$], at the 60 dB HL TEN noise level [F(6,497) = 12.212, $p < .01$], and at the 80 dB HL TEN noise level [F(6,497) = 8.694, $p < .01$]. Scheffe contrast tests were conducted for each TEN noise level to examine further the effect of frequency on the measured SNRs. The results of the multiple comparisons at 40, 60, and 80 dB HL of TEN noise are provided in Tables 10, 11, and 12

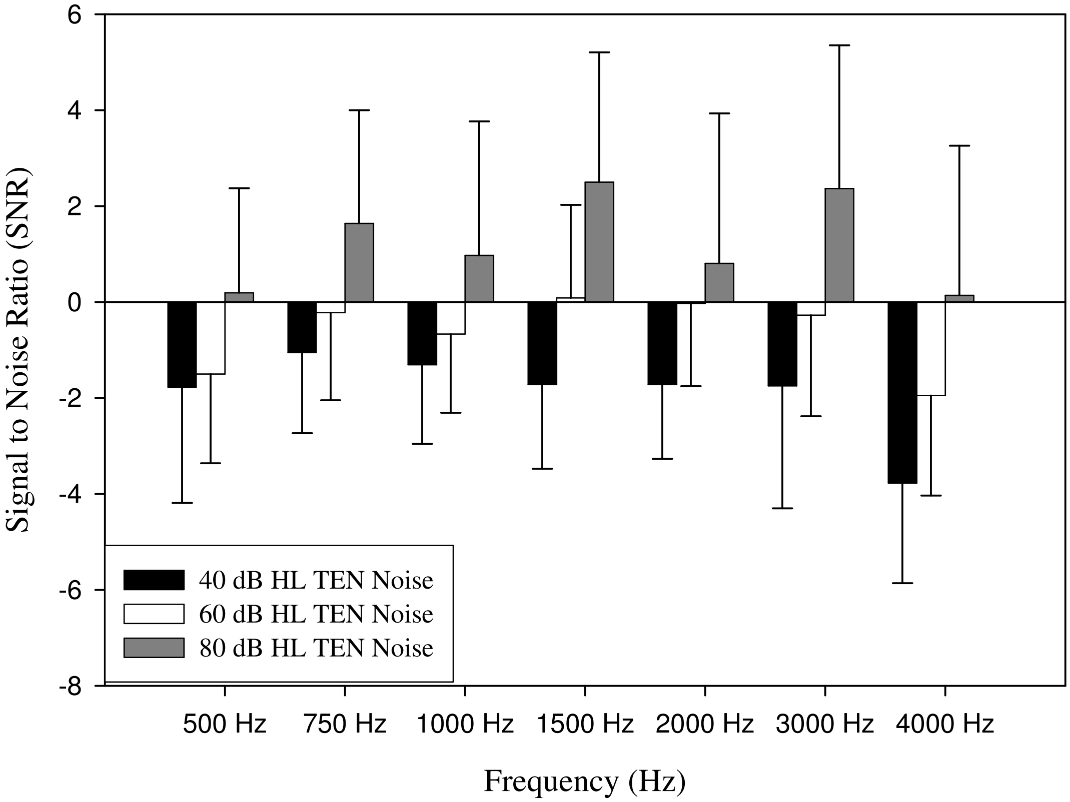

Figure 6. Mean SNRs at each TEN noise level for all seven test frequencies. Error bars indicate one standard deviation.

Table 10

Multiple comparisons using Scheffe post-hoc testing at 40 dB HL TEN noise level at each test frequency

(I) Frequency	(J) Frequency	Mean Difference (I-J)	*p*-value
500 Hz	750 Hz	-0.72222	0.577
	1000 Hz	-0.47222	0.917
	1500 Hz	-0.05556	1.000
	2000 Hz	-0.05556	1.000
	3000 Hz	-0.02778	1.000
	4000 Hz	2.00000	0.000*
750 Hz	500 Hz	0.72222	0.577
	1000 Hz	0.25000	0.997
	1500 Hz	0.66667	0.671
	2000 Hz	0.66667	0.671
	3000 Hz	0.69444	0.625
	4000 Hz	2.72222	0.000*
1000 Hz	500 Hz	0.47222	0.917
	750 Hz	-0.25000	0.997
	1500 Hz	0.41667	0.954
	2000 Hz	0.41667	0.954
	3000 Hz	0.44444	0.937
	4000 Hz	2.47222	0.000*
1500 Hz	500 Hz	0.5556	1.000
	750 Hz	-0.66667	0.671

	1000 Hz	-0.41667	0.954
	2000 Hz	0.00000	1.000
	3000 Hz	0.02778	1.000
	4000 Hz	2.05556	0.000*
2000 Hz	500 Hz	0.05556	1.000
	750 Hz	-0.66667	0.671
	1000 Hz	-0.41667	0.954
	1500 Hz	0.00000	1.000
	3000 Hz	0.02778	1.000
	4000 Hz	2.05556	0.000*
3000 Hz	500 Hz	0.02778	1.000
	750 Hz	-0.69444	0.625
	1000 Hz	-0.44444	0.937
	1500 Hz	-0.02778	1.000
	2000 Hz	-0.02778	1.000
	4000 Hz	2.02778	0.000*
4000 Hz	500 Hz	-2.00000	0.000*
	750 Hz	-2.72222	0.000*
	1000 Hz	-2.47222	0.000*
	1500 Hz	-2.05556	0.000*
	2000 Hz	-2.05556	0.000*
	3000 Hz	-2.02778	0.000*

*$p < .01$

Table 11

Multiple comparisons using Scheffe post-hoc testing at 60 dB HL TEN noise level at each test frequency

(I) Frequency	(J) Frequency	Mean Difference (I-J)	*p*-value
500 Hz	750 Hz	-1.27778	0.013
	1000 Hz	-0.83333	0.325
	1500 Hz	-1.58333	0.000*
	2000 Hz	-1.47222	0.002*
	3000 Hz	-1.22222	0.021
	4000 Hz	0.44444	0.921
750 Hz	500 Hz	1.27778	0.013
	1000 Hz	0.44444	0.921
	1500 Hz	-0.30556	0.988
	2000 Hz	-0.19444	0.999
	3000 Hz	0.05556	1.000
	4000 Hz	1.72222	0.000*
1000 Hz	500 Hz	0.83333	0.325
	750 Hz	-0.44444	0.921
	1500 Hz	-0.75000	0.464
	2000 Hz	-0.63889	0.663
	3000 Hz	-0.38889	0.958
	4000 Hz	1.27778	0.013
1500 Hz	500 Hz	1.58333	0.000*
	750 Hz	0.30556	0.988

	1000 Hz	0.75000	0.464
	2000 Hz	0.11111	1.000
	3000 Hz	0.36111	0.971
	4000 Hz	2.02778	0.000*
2000 Hz	500 Hz	1.47222	0.002*
	750 Hz	0.19444	0.999
	1000 Hz	0.63889	0.663
	1500 Hz	-0.11111	1.000
	3000 Hz	0.25000	0.996
	4000 Hz	1.91667	0.000*
3000 Hz	500 Hz	1.22222	0.021
	750 Hz	-0.05556	1.000
	1000 Hz	0.38889	0.958
	1500 Hz	-0.36111	0.971
	2000 Hz	-0.25000	0.996
	4000 Hz	1.66667	0.000*
4000 Hz	500 Hz	-0.44444	0.921
	750 Hz	-1.72222	0.000*
	1000 Hz	-1.27778	0.013
	1500 Hz	-2.02778	0.000*
	2000 Hz	-1.91667	0.000*
	3000 Hz	-1.66667	0.000*

$^*p < .01$

Table 12

Multiple comparisons using Scheffe post-hoc testing at 80 dB HL TEN noise level at each test frequency

(I) Frequency	(J) Frequency	Mean Difference (I-J)	*p*-value
500 Hz	750 Hz	-1.44444	0.137
	1000 Hz	-0.77778	0.829
	1500 Hz	-2.30556	0.000*
	2000 Hz	-0.61111	0.941
	3000 Hz	-2.16667	0.001*
	4000 Hz	0.05556	1.000
750 Hz	500 Hz	1.44444	0.137
	1000 Hz	0.66667	0.912
	1500 Hz	-0.86111	0.747
	2000 Hz	0.83333	0.776
	3000 Hz	-0.72222	0.874
	4000 Hz	1.50000	0.106
1000 Hz	500 Hz	0.77778	0.829
	750 Hz	-0.66667	0.912
	1500 Hz	-1.52778	0.093
	2000 Hz	0.16667	1.000
	3000 Hz	-1.38889	0.174
	4000 Hz	0.83333	0.776
1500 Hz	500 Hz	2.30556	0.000*
	750 Hz	0.86111	0.747

	1000 Hz	1.52778	0.093
	2000 Hz	1.69444	0.038
	3000 Hz	0.13889	1.000
	4000 Hz	2.36111	0.000*
2000 Hz	500 Hz	0.61111	0.941
	750 Hz	-0.83333	0.776
	1000 Hz	-0.16667	1.000
	1500 Hz	-1.69444	0.038
	3000 Hz	-1.55556	0.081
	4000 Hz	0.66667	0.912
3000 Hz	500 Hz	2.16667	0.001*
	750 Hz	0.72222	0.874
	1000 Hz	1.38889	0.174
	1500 Hz	-0.13889	1.000
	2000 Hz	1.55556	0.081
	4000 Hz	2.22222	0.001*
4000 Hz	500 Hz	-0.05556	1.000
	750 Hz	-1.50000	0.106
	1000 Hz	-0.83333	0.776
	1500 Hz	-2.36111	0.000*
	2000 Hz	-0.66667	0.912
	3000 Hz	-2.22222	0.001*

*$p < .01$

respectively. As indicated in Table 10, there was a significant difference between 4000 Hz and all other test frequencies when the 40 dB HL TEN noise level was employed. At this frequency, the SNR was better (lower) than that observed at all other frequencies. There were no significant differences found between any other frequencies at this TEN noise level. Table 11 (60 dB HL TEN noise) also indicates a significant difference between 4000 Hz and all other test frequencies with the exception of 500 Hz. A significant difference was also demonstrated between 500 Hz and 1500 Hz, and between 500 Hz and 2000 Hz. Finally, Sheffe contrast tests revealed a significant difference between 500 and 1500 Hz, and between 500 Hz and 3000 Hz at 80 dB HL TEN noise (see Table 12). A significant difference was also found between 4000 and 1500 Hz and between 4000 Hz and 3000 Hz at the 80 dB HL TEN noise level. Overall, the data indicate that the greatest differences in SNRs at all three TEN noise levels are between the lowest test frequency (500 Hz) and selected other frequencies, and between the highest test frequency (4000 Hz) and most other frequencies.

A simple main effects analysis was conducted separately at each frequency to determine the effect of TEN noise level. A significant effect of TEN noise level was observed at each frequency (see Table 13). Consequently, multiple comparisons of the three TEN noise levels using Scheffe post-hoc testing were conducted at each frequency. The specific results of these comparisons are listed in Table 14. As Table 14 shows, there is a significant difference between all three noise levels at 1500, 3000, and 4000 Hz. Interestingly, there was only a significant difference found between the highest TEN noise level (80 dB HL) and the other two noise levels (40 and 60 dB HL) at 500, 750 and 1000 Hz. No significant differences were found between 40 dB HL and 60 dB HL of

Table 13

Results of one-way ANOVAs of TEN noise level at each of seven test frequencies

Frequency	*F*	*df*	*p*-value
500 Hz	17.553	2, 213	0.000*
750 Hz	35.127	2, 213	0.000*
1000 Hz	22.588	2, 213	0.000*
1500 Hz	68.556	2, 213	0.000*
2000 Hz	23.656	2, 213	0.000*
3000 Hz	47.105	2, 213	0.000*
4000 Hz	44.929	2, 213	0.000*

*$p < .01$

Table 14

Multiple comparisons using Scheffe post-hoc testing at all seven test frequencies for the three TEN noise levels

(I) TEN noise level	(J) TEN noise level	Mean Difference (I-J)	*p*-value
		500 Hz	
40 dB HL	60 dB HL	-0.27778	0.743
	80 dB HL	-1.97222	0.000*
60 dB HL	40 dB HL	0.27778	0.743
	80 dB HL	-1.69444	0.000*
80 dB HL	40 dB HL	1.97222	0.000*
	60 dB HL	1.69444	0.000*
		750 Hz	
40 dB HL	60 dB HL	-0.83333	0.043
	80 dB HL	-2.69444	0.000*
60 dB HL	40 dB HL	0.83333	0.043
	80 dB HL	-1.86111	0.000*
80 dB HL	40 dB HL	2.69444	0.000*
	60 dB HL	1.86111	0.000*
		1000 Hz	
40 dB HL	60 dB HL	-0.63889	0.191
	80 dB HL	-2.27778	0.000*
60 dB HL	40 dB HL	0.63889	0.191
	80 dB HL	-1.63889	0.000*
80 dB HL	40 dB HL	2.27778	0.000*

	60 dB HL	1.63889	0.000*
1500 Hz			
40 dB HL	60 dB HL	-1.80556	0.000*
	80 dB HL	-4.22222	0.000*
60 dB HL	40 dB HL	1.80556	0.000*
	80 dB HL	-2.41667	0.000*
80 dB HL	40 dB HL	4.22222	0.000*
	60 dB HL	2.41667	0.000*
2000 Hz			
40 dB HL	60 dB HL	-1.69444	0.000*
	80 dB HL	-2.52778	0.000*
60 dB HL	40 dB HL	1.69444	0.000*
	80 dB HL	-0.83333	0.087
80 dB HL	40 dB HL	2.52778	0.000*
	60 dB HL	0.83333	0.087
3000 Hz			
40 dB HL	60 dB HL	-1.47222	0.003*
	80 dB HL	-4.11111	0.000*
60 dB HL	40 dB HL	1.47222	0.003*
	80 dB HL	-2.63889	0.000*
80 dB HL	40 dB HL	4.11111	0.000*
	60 dB HL	2.63889	0.000*

4000 Hz			
40 dB HL	60 dB HL	-1.83333	0.000*
	80 dB HL	-3.91667	0.000*
60 dB HL	40 dB HL	1.83333	0.000*
	80 dB HL	-2.08333	0.000*
80 dB HL	40 dB HL	3.91667	0.000*
	60 dB HL	2.08333	0.000*

*$p < .01$

TEN noise at these test frequencies.

Overall, as can be seen in the figures representing the significant two-way interactions in this study, the variability in SNR performance across measures was very low. This may be because all participants, including the older group, demonstrated normal to near-normal hearing sensitivity or because of the more restricted (2 dB) final step size employed.

Pure-tone thresholds in Quiet

The TEN (HL) CD (Moore et al., 2004) was utilized to measure pure-tone audiometric thresholds at each of the seven test frequencies (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz) without the presence of any TEN noise. This measure was conducted twice. These pure-tone thresholds were analyzed using a mixed ANOVA with two within-subjects factors (frequency and trial) and one between-subjects factor (group). Only the results for frequency violated Mauchly's Test for Sphericity. Consequently, for frequency, the Greenhouse Geisser correction was applied for the degrees of freedom. Results of this mixed ANOVA (shown in Table 15) revealed significant main effects (all at a significance level of $p < .01$) of group and frequency and a significant interaction between group and frequency. No main effect of trial was found.

Post-hoc testing for the interaction of group and frequency [F(6,204) = 4.209, $p < .01$] was conducted to determine the effect of group for each of the seven test frequencies and the effect of frequency for each group. Figure 6 shows the mean pure-tone thresholds measured with the TEN (HL) CD for the younger and older group at each of the seven test frequencies. As the figure illustrates, the older group demonstrated poorer (higher) pure-tone thresholds across test frequencies compared to the younger

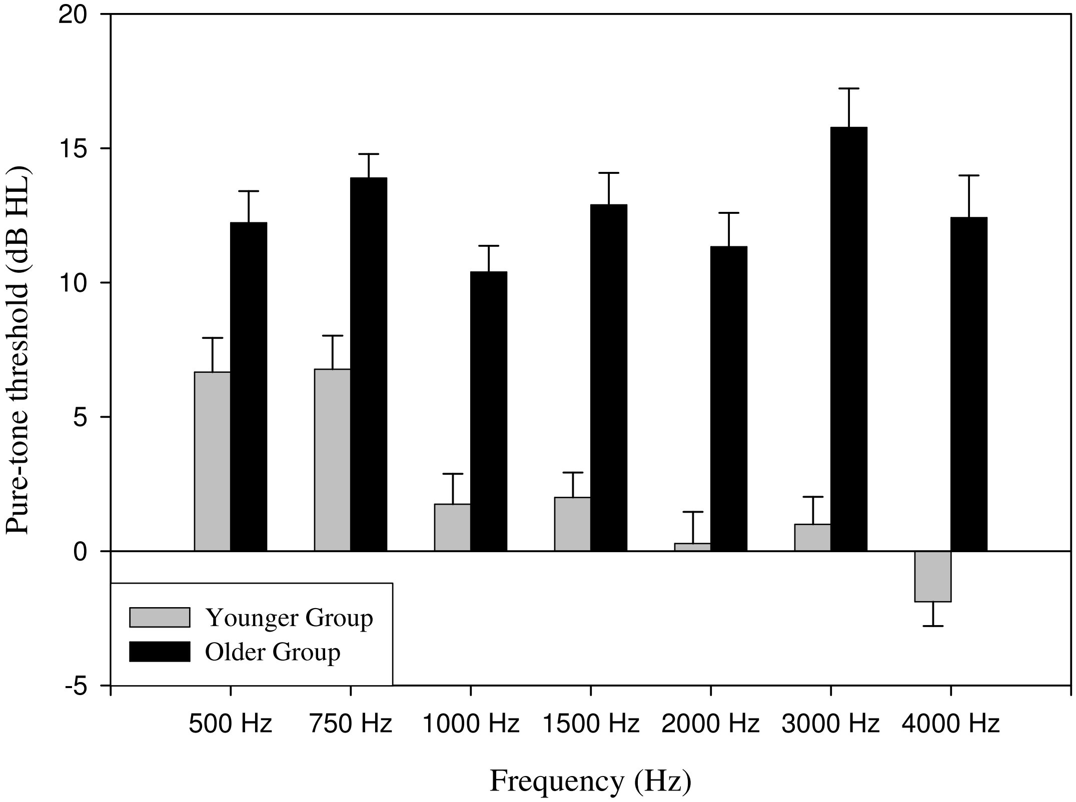

Figure 7. Pure-tone thresholds measured using the TEN (HL) CD for both groups (n = 18/group) at each of seven test frequencies. Error bars indicate the standard error of the mean.

Table 15

Summary of mixed ANOVA results for pure-tones in quiet using TEN (HL) CD

Variables	*F*	*df*	*p*-value
Group	37.191	1, 34	0.000*
Trial	2.993	1, 34	0.093
Frequency	5.231	3.269, 111.162	0.002*
Trial * Group	0.324	1, 34	0.573
Frequency * Group	4.209	6, 204	0.001*
Trial * Frequency	0.998	6, 204	0.428
Trial * Frequency * Group	0.960	6, 204	0.453

*$p < .01$

Table 16

Results of independent samples t-tests showing the difference in pure-tone thresholds measured in quiet using the TEN (HL) CD between the younger and older groups at each of seven test frequencies

Frequency	*t*	*df*	*p*-value
500 Hz	-3.207	70	0.002
750 Hz	-4.663	70	0.000*
1000 Hz	-5.810	70	0.000*
1500 Hz	-7.248	70	0.000*
2000 Hz	-6.412	70	0.000*
3000 Hz	-8.333	70	0.000*
4000 Hz	-7.921	70	0.000*

*$p < .001$

Table 17

Multiple comparisons using Scheffe post-hoc testing for the younger group at each test frequency

(I) Frequency	(J) Frequency	Mean Difference (I-J)	*p*-value
500 Hz	750 Hz	-0.11111	1.000
	1000 Hz	4.91667	0.132
	1500 Hz	4.66667	0.180
	2000 Hz	6.38889	0.012
	3000 Hz	5.66667	0.043
	4000 Hz	8.55556	0.000*
750 Hz	500 Hz	0.11111	1.000
	1000 Hz	5.02778	0.113
	1500 Hz	4.77778	0.157
	2000 Hz	6.50000	0.009*
	3000 Hz	5.77778	0.036
	4000 Hz	8.66667	0.000*
1000 Hz	500 Hz	-4.91667	0.132
	750 Hz	-5.02778	0.113
	1500 Hz	-0.25000	1.000
	2000 Hz	1.47222	0.989
	3000 Hz	0.75000	1.000
	4000 Hz	3.63889	0.489
1500 Hz	500 Hz	-4.66667	0.180

	750 Hz	-4.77778	0.157
	1000 Hz	0.25000	1.000
	2000 Hz	1.72222	0.975
	3000 Hz	1.00000	0.999
	4000 Hz	3.88889	0.401
2000 Hz	500 Hz	-6.38889	0.012
	750 Hz	-6.50000	0.009*
	1000 Hz	-1.47222	0.989
	1500 Hz	-1.72222	0.975
	3000 Hz	-0.72222	1.000
	4000 Hz	2.16667	0.925
3000 Hz	500 Hz	-5.66667	0.043
	750 Hz	-5.77778	0.036
	1000 Hz	-0.75000	1.000
	1500 Hz	-1.00000	0.999
	2000 Hz	0.72222	1.000
	4000 Hz	2.88889	0.752
4000 Hz	500 Hz	-8.55556	0.000*
	750 Hz	-8.66667	0.000*
	1000 Hz	-3.63889	0.489
	1500 Hz	-3.88889	0.401
	2000 Hz	-2.16667	0.925
	3000 Hz	-2.88889	0.752

group. Figure 6 further shows that the younger group demonstrated different pure-tone thresholds across test frequencies, appearing to have poorer (higher) pure-tone thresholds at the lower frequencies and better (lower) pure-tone thresholds at the higher frequencies.

Results of pairwise comparisons, shown in Table 16, indicate a significant difference ($p < .001$ after adjusting for Bonferroni correction for multiple t-tests) in pure-tone threshold, between groups, at all frequencies above 500 Hz. A simple main effects analysis was conducted to evaluate the effect of frequency for the younger group and the older group. A significant effect of frequency was found for the younger group [F (6,251) = 8.624, $p < .01$]. The effect of frequency for the older group was not significant [F (6,251) = 2.015, $p = .064$]. Multiple comparisons tests (Scheffe) were conducted for the younger group to determine the significance of the differences observed in pure-tone thresholds between each pair of frequencies. These results are shown in Table 17. As can be seen from the table, there were significant differences in pure-tone thresholds for the younger group between both 500 Hz and 750 Hz and the three higher test frequencies (2000, 3000, and 4000 Hz).

Pure-tone thresholds measured using standard clinical technique versus TEN (HL) CD

A paired samples t-test was conducted at four test frequencies to evaluate if there was a difference observed in pure-tone thresholds measured using a standard clinical technique versus pure-tone thresholds measured using the TEN (HL) CD. Because no effect of trial was found for the pure-tone thresholds measured using the TEN (HL) CD, these pure-tone results were collapsed at each frequency and for both groups. Comparisons could only be conducted at 500, 1000, 2000, and 4000 Hz because inter-octave frequencies were not tested using the standard audiometric technique for measuring pure-tone

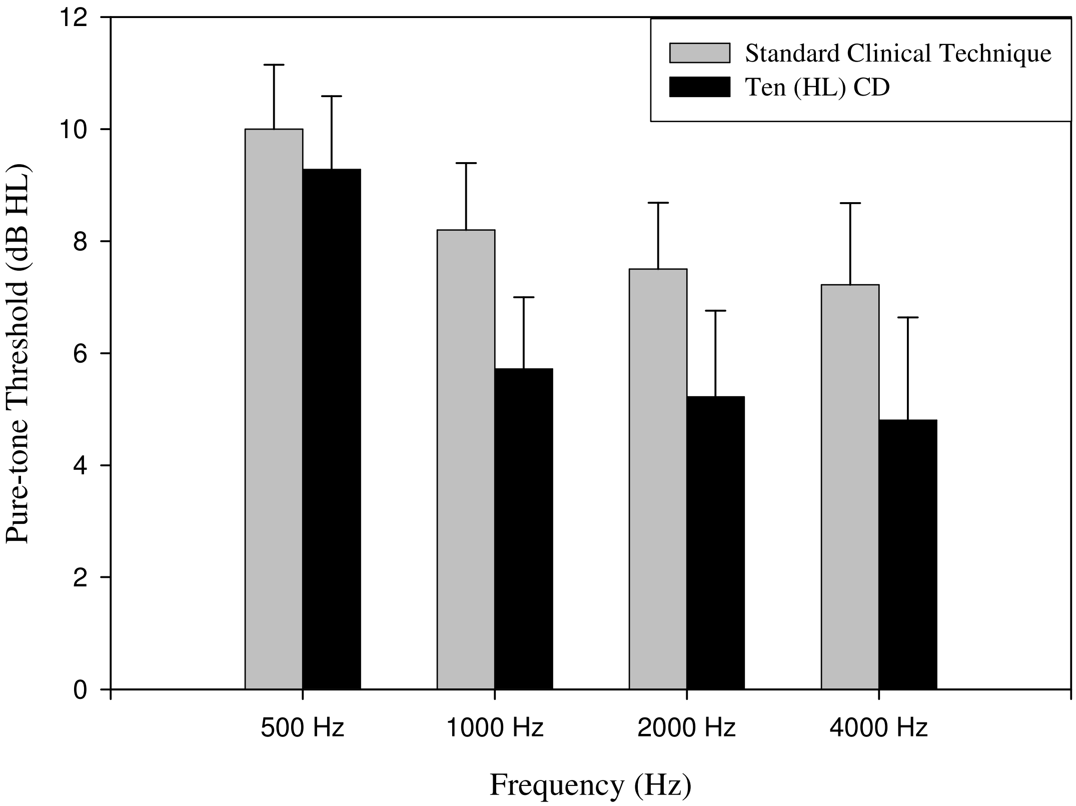

Figure 8. Pure-tone threshold results measured using a standard clinical technique and measured using the TEN (HL) CD at four test frequencies. Error bars indicate the standard error of the mean.

Table 18

Results of paired samples t-tests showing the difference in pure-tone thresholds measured in quiet using the TEN (HL) CD and measured by a standard clinical technique

Frequency	*t*	*df*	*p*-value
500 Hz	1.125	35	0.268
1000 Hz	4.473	35	0.000*
2000 Hz	3.401	35	0.002*
4000 Hz	3.002	35	0.005

$^*p < .003$

frequencies are shown in Figure 7. As the figure illustrates, pure-tone thresholds are poorer (higher) at all frequencies using the standard clinical method for measuring pure-tone thresholds compared to the pure-tone thresholds measured with the TEN (HL) CD. Paired samples t-tests conducted at each frequency revealed a significant difference in pure-tone thresholds using the two methods at 1000 and 2000 Hz. The Bonferroni correction factor for multiple *t*-tests was applied. These results are shown in Table 18. As the table shows, no significant difference was found in pure-tone thresholds between the two methods at 500 Hz and 4000 Hz. While the difference between these two methods was found to be significant at two out of the four test frequencies, it should be noted that the two methods utilized a different method for determining the final pure-tone threshold. More specifically, the final step size was more specific (2 dB) when measuring pure-tone thresholds with the TEN (HL) CD compared to the final step size for the standard clinical technique (5 dB). Therefore, the poorer (higher) pure-tone thresholds observed using the standard clinical technique may be due to the different step sizes employed by the two techniques for determining final threshold.

Relationship between age and pure-tone threshold on SNR

The test results above show significant differences between the two age groups on all pure-tone measures. However, the results also indicate that these two age groups have significantly different pure-tone thresholds, despite the fact that they both have clinically normal to near-normal hearing sensitivity. A multiple regression analysis was therefore conducted to determine if the variance in performance on the SNR measure could be accounted for primarily by age or by hearing level, or by some combination of the two. To that end, stepwise multiple regression analyses were conducted at the seven test frequencies for the three TEN noise levels. The criterion variable was the SNR, and the predictor variables were age and pure-tone threshold as measured using the TEN (HL) CD. The pure-tone threshold used was the same frequency as the SNR measure. These analyses, shown in Table 19, indicated that the two predictor variables did not significantly account for any of the variance at 750 Hz (60 dB TEN noise level only), 1000 Hz (40 dB TEN noise level only), and 2000 Hz (60 and 80 dB TEN noise levels). However, age was the predictor variable that accounted for most of the variance on SNR measures for most of the other test frequencies and levels. These analyses suggest that while there were differences demonstrated between the pure-tone thresholds of both groups, these hearing sensitivity differences did not significantly contribute to the variance in SNR measures found at most frequencies. Therefore, the difference in hearing sensitivity observed between the two groups at almost all test frequencies, while being statistically different from each other, did not contribute to the different SNRs observed between the groups at these frequencies. Rather, listener age was the primary variable contributing to the variance in SNR at most frequencies and levels.

Table 19

Summary of stepwise multiple regression analyses for variables predicting SNR in TEN noise (final model only)

Variable	r^2	*F*	*p*-value
500 Hz (40 dB HL)			
Age	0.187	7.808	0.008**
500 Hz(60 dB HL)			
Age	0.314	15.545	0.000**
500 Hz (80 dB HL)			
Age	0.337	15.404	0.000**
Pure-tone threshold	0.483		
750 Hz (40 dB HL)			
Pure-tone threshold	0.307	15.061	0.000**
750 Hz (60 dB HL)	______	_______	_______
750 Hz (80 dB HL)			
Age	0.176	7.248	0.011*
1000 Hz (40 dB HL)	______	_______	________
1000 Hz (60 dB HL)			
Pure-tone threshold	0.209	8.984	0.005**
1000 Hz (80 dB HL)			
Age	0.453	20.276	0.000**
Pure-tone threshold	0.524		

1500 Hz (40 dB HL)			
Pure-tone threshold	0.308	15.167	0.000**
1500 Hz (60 dB HL)			
Age	0.115	4.398	0.043*
1500 Hz (80 dB HL)			
Age	0.134	5.259	0.028*
2000 Hz (40 dB HL)			
Pure-tone threshold	0.288	13.766	0.001**
2000 Hz (60 dB HL)	______	______	______
2000 Hz (80 dB HL)	______	______	______
3000 Hz (40 dB HL)			
Age	0.303	14.785	0.001**
3000 Hz (60 dB HL)			
Age	0.254	11.553	0.002**
3000 Hz (80 dB HL)			
Age	0.284	13.511	0.001**
4000 Hz (40 dB HL)			
Age	0.380	20.874	0.000**
4000 Hz (60 dB HL)			
Age	0.210	9.058	0.005**
4000 Hz (80 dB HL)			
Age	0.210	9.058	0.005**

*$p < .05$; **$p < .01$

Chapter 6: Discussion

Age-Effects

The purpose of this study was to investigate the effects of age on the TEN (HL) test (Moore et al., 2004) for normal to near-normal hearing listeners. Analysis of signal-to-noise ratio (SNR) performance, as measured on the TEN (HL) test, revealed significant main effects of age group. The effect of age varied with TEN noise level and with frequency. These interaction effects are described below.

Age x TEN Noise Level Interaction.

Further analysis of the interaction between group and TEN noise level revealed that the younger group consistently performed better than the older group at all three TEN noise levels employed (40 dB HL, 60 dB HL, and 80 dB HL of TEN noise). The source of the interaction effect appears to be related to the magnitude of the difference in performance between the two age groups, which was greatest at 80 dB HL of TEN noise. There are no previous studies that have investigated the effects of age on SNR performance for various levels of TEN noise, making direct comparisons with the findings from the current study difficult. However, previous studies (Burkard & Sims, 2002; Dubno et al., 2002) have examined age-related differences at different levels of masking noise.

In the study by Dubno et al. (2002), eight younger (aged 20-27 years) and eight older (aged 60-74 years) normal to near-normal hearing participants were evaluated using a simultaneous masking paradigm. Tonal signals (350 ms duration) were presented simultaneously in a speech-shaped steady-state noise masker at 77 dB SPL and 85 dB SPL. Results revealed masked thresholds to be 1-2 dB higher (poorer) for the older group compared to the younger group for both noise levels, but this difference was not statistically significant (Dubno et al., 2002).

These findings differ from the current study in that no significant differences in masked thresholds between the two age groups were demonstrated. It is possible that the slight difference in performance observed for the older group in the Dubno et al. (2002) study did not reach statistical significance because of the small number of participants in each group (n = 8 / group). The current study had more than twice the number of participants in each group (n = 18 / group). Further, Dubno and colleagues (2002) did not analyze the differential effect of noise level, but inspection of the figure from the study suggested that none existed. The two masking levels (77 and 85 dB SPL) are similar, higher levels of noise. Notably, both noise levels are similar in intensity to the highest noise level (80 dB HL) employed in the current study, but yielded different age-related findings. This again could be influenced by the smaller number of participants and/or to the different type of masking noise used in the Dubno et al. (2002) study.

Burkard and Sims (2002) investigated the effects of different levels of masking noise on the auditory brainstem response (ABR) of younger and older normal to near-normal hearing listeners. Click stimuli were presented in quiet and simultaneously with a broadband noise at six different effective masking (EM) levels: 20, 30, 40, 50, 60, and 70 dB EM. Age differences were observed primarily for wave I amplitudes, but these differences were largest in the "no-noise" condition and in the low levels of EM noise. The results showed a decrease in wave I amplitudes for the younger group when masking noise was at 20-30 dB EM and above; wave I amplitudes were relatively stable across noise level and decreased at the highest level (70 dB EM) for the older group (Burkard &

Sims, 2002). Thus, age-related differences were greater in low levels of the noise and were minimal in higher levels of noise, which is inconsistent with the findings from the current investigation.

The current study and that of Burkard and Sims (2002) employed two different measures (one behavioral and the other physiological). As noted above, both studies demonstrated group differences across different levels of masking noise, but in opposite directions. The greatest difference between the two groups in the Burkard and Sims (2002) study was observed in the "no noise" condition and in conditions with lower levels of EM noise, whereas the greatest difference between the two groups in the current study was observed at the highest TEN noise level. Further, the older group (Burkard & Sims, 2002) demonstrated relatively stable wave I amplitudes across noise level, revealing the greatest reduction in wave I amplitude at the highest level (70 dB EM). Only the younger group demonstrated increasingly smaller wave I amplitudes with increasing EM noise level. The smaller amplitudes observed for the older group compared to the younger group at all masking levels may be due to poorer hearing sensitivity for the older group. In the current study, the older group (as well as the younger group) demonstrated increasingly poorer (higher) SNR performance as the TEN noise levels increased.

Obviously, differences between the current study and the studies by Burkard and Sims (2002) and Dubno et al. (2002) exist. Some of these differences include different types of masking noise, different methods utilized to measure threshold response, different masker levels, different outcome measures, and different response methods. The current study differed from the Burkard and Sims (2002) and Dubno et al. (2002)

study in that age-effects were demonstrated between the two groups at all noise levels, with the greatest difference at the highest noise level (80 dB HL). The participants in the current study had normal to near-normal hearing sensitivity, therefore the differences observed between the two groups are most likely related to age differences.

There are several possible sources for these age-related differences. One possibility is that the older participants have poorer processing efficiency or detection efficiency (Aazh & Moore, 2007; Gifford & Bacon, 2005; Moore et al., 2000; Patterson et al., 1982). Another possible explanation is that older individuals demonstrate more conservative responses than younger individuals on signal detection tasks (Potash & Jones, 1977; Rees & Botwinick, 1971). A final source of the age-related differences on signal detection-in-noise tasks may be that older individuals' auditory filters are broader compared to those of younger listeners (Patterson et al., 1982). This would result in poorer (higher) SNRs observed for the older group compared to the younger group.

Processing efficiency, or detection efficiency, refers to an individual's ability to detect a signal presented in noise. It is calculated, therefore, as the signal-to-noise ratio at threshold (Gifford & Bacon, 2005). It is believed that two listeners can have similar auditory filters but demonstrate different processing efficiency (Patterson et al., 1982). For example, a less efficient listener may require that a signal be presented at a greater intensity to detect it when it is presented in a noise masker, thus increasing the SNR at the output of their auditory filter. In this way, the less efficient listener demonstrates a higher SNR at threshold than the more efficient listener although both listeners can have similar audiometric thresholds. Processing efficiency is believed to be related to auditory processing (central processes) as well as cognitive factors such as memory, learning, and attention (Gifford & Bacon, 2005; Patterson et al., 1982).

Because processing efficiency is not dependent on peripheral mechanisms such as hearing sensitivity, individual variation in processing efficiency can be observed among individuals with normal hearing as well. Processing efficiency is believed to worsen with increasing age (Patterson et al., 1982; Peters & Moore, 1992). In a study by Moore et al. (1992), processing efficiency (measured as SNR required at threshold) was found to be significantly higher for the older normal hearing group (n = 11) aged 62 – 83 years than for the younger normal hearing group (n = 11) at four center frequencies (100, 200, 400, and 800 Hz) (Moore et al., 1992). A similar finding was reported in a study by Gifford and Bacon (2005). In this study, the SNRs were approximately 9 dB higher for older normal-hearing listeners compared to younger normal-hearing participants. The younger group (aged 19-30 years) was matched to an older group (aged 60-75 years) of participants on the basis of hearing sensitivity. All participants had normal hearing sensitivity. Therefore, the authors attributed the differences in SNRs observed between the two groups to age-related deficits in processing efficiency of the older group (Gifford & Bacon, 2005). Because all of the participants in the current study demonstrated similar hearing sensitivity and only differed on age, it is possible that the older group of listeners demonstrated poorer (higher) SNRs due to poorer processing efficiency.

Poorer processing efficiency has also been cited in the literature as a possible explanation for unusual results on the TEN test (Aazh & Moore, 2007; Summers et al., 2003). Individuals who demonstrate poorer-than-normal processing efficiency may explain conflicting results between PTC and TEN test measurements when the PTC suggests no dead region but the TEN test suggests a dead region. If an individual has poor processing efficiency, he or she could demonstrate higher masked thresholds on the TEN test (indicative of a dead region) without altering the tip of the PTC at the same frequency (suggesting no dead region) (Summers et al., 2003). Aazh and Moore (2007) attributed the variability in SNR performance observed for older individuals to have dead regions and those found not to have dead regions to the possibility of poor processing efficiency (or detection efficiency). All participants in the Aazh and Moore (2007) study were aged 63-101 years. The researchers noted that of the 36 ears meeting the criteria for a dead region at 4000 Hz, 11 ears only just met the recommended criteria (SNRs of 10 or 11 dB). Also, of the 62 ears with no dead regions, 11 ears just failed to meet the recommended criteria for a dead region (SNRs of 8 or 9 dB). Because variability is expected with measures of masked thresholds and because detection efficiency has been found to worsen with age (Patterson et al., 1982; Peters & Moore, 1992), the authors attributed the variability observed in the performance of both groups of participants to poorer processing efficiency (Aazh & Moore, 2007).

Another explanation for the age differences observed in the present study despite similar hearing sensitivity could be related to the use of a more conservative response criterion by older listeners on a signal detection task. Previous investigators (Potash & Jones, 1977; Rees & Botwinick, 1971) observed that older listeners exhibited poorer pure-tone detection thresholds than younger listeners in a broadband noise masker. However, these investigators analyzed the sensitivity and response criteria of listeners in the younger and older groups, and observed that while the two groups had similar sensitivity in detecting a signal, the older listeners employed a more conservative response criterion. The net effect of this conservative response strategy is that older listeners do not respond when they are unsure of the presence of a signal (in order to avoid being wrong). As a result, thresholds appear to be poorer than the listener's sensitivity would suggest.

According to the theory of signal detection (Tanner & Swets, 1954, Swets, 1961), in order to separate the effects of sensitivity from response criterion, the investigator must employ a two-interval forced choice signal-in-noise task, in which the listener responds either "noise" (when the listener perceives the signal is not present) or "signal + noise" (when the listener perceives the signal is present). The signal is presented in some trials but not in others (Marshall & Jesteadt, 1986; Potash & Jones, 1977; Rees & Botwinick, 1971). The TEN (HL) test, however, uses a modified method of limits to determine threshold because this is the method used in routine clinical audiological practice. This method does not permit the investigator to separate the listener's response bias from their sensitivity to the signal. Therefore, if the listener opted to employ a more conservative response bias, but the listener was still responding to the signal in a logical manner, the investigator would be unable to separate the sensitivity from the response bias of the listener. The investigator using this method would have to accept the responses as being indicative of the listener's true ability. Conversely, if the listener employed a more lax criterion, the investigator, or audiologist, may identify this behavior because the participant demonstrates a high number of false-positive responses. Therefore, the higher (poorer) SNR performance for the older group could possibly be attributed to this group applying a more conservative internal criterion compared to the younger group in the current study; however, the clinical method employed by the TEN (HL) test does not allow for direct assessment of this response criterion.

A third possible reason for the observed age-related differences in the current study may be differences in auditory filters between young and older listeners. Patterson and his colleagues (1982) demonstrated that auditory filters become broader (deteriorate) as age increases. Therefore, due to these broader auditory filters, it becomes increasingly more difficult for the listener to distinguish signals from noise. This may explain why the older group demonstrated poorer (higher) SNRs compared to the younger group at all levels of the TEN noise, despite similar hearing sensitivity. While previous research (Patterson et al., 1982) has demonstrated that auditory filters broaden with increasing age, other studies have observed no age-related difference in auditory filters between young and older normal hearing adults (Peters & Hall; Sommers & Gehr, 1998; Sommers & Humes, 1993). Therefore, while it is possible that broader auditory filters may have contributed to the older group demonstrating poorer (higher) SNRs compared to the younger group in TEN noise despite similar hearing sensitivity in the current study, the conflicting findings of previous research suggest that this apparent peripheral mechanism may not be the only factor contributing to the age-related differences observed.

One possible interpretation of the current findings is that the two age groups exhibited differences in SNR performance because of differences in pure-tone thresholds, rather than to age. To that end, multiple regression analyses were conducted to determine whether the primary factor contributing to the results was hearing sensitivity or age. The multiple regression analyses revealed that the source of the variance observed in SNRs was accounted for primarily by the difference in age between the two groups, rather than to the differences in hearing sensitivity. Thus, the poorer (higher) SNR performance observed for the older group compared to the younger group on the TEN (HL) test in this study is attributed to age effects.

Group x Frequency Interaction.

A significant interaction of group and frequency was found in the current study. The results revealed that the younger group performed better (lower SNR) at each test frequency compared to the older group. The source of the interaction appears to be different SNR performance patterns across frequency for the two groups. More specifically, the greatest difference between test frequencies was demonstrated for both groups at the highest test frequency (4000 Hz) (and between 500 Hz and two other frequencies for the younger group). Interestingly, both groups exhibited the best (lowest SNR) at 4000 Hz compared to the other test frequencies. The significant difference in group performance was surprising because the TEN (HL) test was designed to produce equal masked thresholds across frequency (500-4000 Hz) for normal hearing individuals (Moore et al., 2004). Both groups of participants in the current study demonstrated normal to near-normal hearing sensitivity across these test frequencies. Therefore, the significantly different SNR performance for the two groups across test frequency was not expected.

Dubno et al. (2002) observed age-related differences in masked thresholds across stimulus frequency between younger and older adults with normal to near-normal hearing. In this study, masked thresholds for 20-ms tones were evaluated at four test frequencies (500, 1000, 2000, and 4000 Hz) compared to the current study which evaluated masked thresholds for 1-2 sec tones at seven test frequencies (500, 750, 1000, 1500, 2000, 3000, and 4000 Hz). Dubno et al. (2002) reported that masked thresholds, using a broadband noise masker (simultaneous masking paradigm), were significantly higher (3-4 dB) for the older group compared to the younger group when averaged across frequency. Dubno et al. (2002) did not compare the performance of the two groups at each of the test frequencies, therefore it is not certain whether these group differences were significantly greater for any one test frequency compared to another. Overall, the findings are consistent across the two studies, showing that older listeners exhibited poorer detection thresholds in broadband noise than younger listeners across a range of frequencies.

Effects of TEN noise level

As greater levels of the TEN noise were used, both groups demonstrated poorer (higher) SNRs. This trend is illustrated in Figure 3. As the figure indicates, both groups had the lowest SNRs when listening in the 40 dB HL of TEN noise. Their SNRs were poorer (higher) at the 60 dB HL of TEN noise and the SNRs of both groups were clearly poorest (highest SNRs) at the 80 dB HL of TEN noise. The greatest difference in SNR performance between the two age groups was demonstrated at this highest TEN noise level.

The criteria for the diagnosis of a dead region were derived from results of normal to near-normal hearing listeners on the older version (TEN (SPL)) of the test, which provided calibration in dB SPL (Moore et al., 2000). In this early study (Moore et al., 2000), three levels of the TEN noise (30, 50, and 70 dB SPL) were employed. The authors found that two different groups of younger listeners (n = 12 and n = 10) with normal to near-normal hearing demonstrated masked thresholds close to the level of TEN noise for each of the three TEN noise levels (across test frequency). Therefore, when listening in 70 dB SPL of TEN noise, the masked thresholds were close to (within 95 % confidence intervals) 70 dB SPL across test frequency (i.e., SNR = 0 dB). Both groups exhibited similar performance patterns for all three TEN noise levels (Moore et al., 2000).

A subsequent study conducted by Moore and colleagues (2003) evaluated the effect of TEN noise level on the performance of a group of young normal-hearing participants (n = 16, mean age = 25 years). Three TEN noise levels (30, 50, and 70 dB SPL) were used. The results revealed mean masked thresholds that were within 5 dB (+/- 5 dB SNR) of the TEN noise level employed, although no statistical analyses were provided between the three TEN noise levels (Moore et al., 2003).

The current study found a significant difference between SNRs measured at the three noise levels on the TEN (HL) test. Theoretically, listeners with normal hearing should show SNRs of 0 dB, regardless of TEN noise level, and hence, there should be no effect of noise level on the TEN test for these listeners. In practice, individual variability is expected with measures of masked threshold allowing for normal hearing listeners to demonstrate slightly different SNRs around the mean, regardless of TEN noise level, which are considered “normal” performance (or more importantly not indicative of a dead region). Differences in processing efficiency (mentioned above) may contribute to this range of normal performance. The actual mean SNRs observed at all three TEN noise levels were within the recommended criteria for individuals with no dead region (i.e., SNRs +10 dB above the TEN noise level and +10 dB above the threshold in quiet) (Moore et al., 2000; Moore et al. 2004). That is, the poorest (highest) mean SNR was less than 3 dB SNR. Therefore, the results of the current study are in agreement with the normative results of previous studies when applied clinically (Moore et al., 2000; Moore et al., 2003; Moore et al., 2004) despite the observation of significant differences in SNR at different noise levels.

Effects of Frequency

The TEN (HL) test was designed to produce equal masked thresholds across test frequencies for normal hearing listeners and listeners with sensorineural hearing loss but no dead regions (Moore et al., 2004). Therefore it was hypothesized that no effect of frequency would be observed, if the TEN (HL) test is believed to be a valid test. The findings in this study showed a significant difference in SNR performance across frequencies, which differs from previous findings (Moore et al, 2000; Moore et al., 2004). Although these results across the two studies (Moore et al., 2000; Moore et al., 2004) and the current study appear to disagree, an examination of the mean data indicates the findings of the current study are similar to the previous studies in that the mean SNR values were never greater than 10 dB at any frequency (indicative of a dead region) and the range of mean SNR values (minimum = -3 dB SNR; maximum = < +2 dB SNR) were close to the findings of the younger normal hearing group in the study by Moore et al. (2004) across frequency. It was also interesting that both participant groups in the current study performed the best (lowest SNRs) at the highest test frequency (4000 Hz).

In creating the TEN (HL) noise, the authors reported a slight difference in mean masked thresholds observed for 4000 Hz compared to the other test frequencies. This difference resulted in slightly higher (1.6 dB) SNRs for the normative group of young to middle-aged normal to near-normal hearing listeners (Moore et al., 2004). Consequently, the authors applied a “correction” factor at 4000 Hz in the final version of the TEN (HL) noise, and noted that this did not correct for the variability in masked threshold observed at this frequency compared to the other frequencies. More specifically, the range of performance in masked threshold varied from 56 – 66 dB HL (-4 to +6 dB SNR) at this frequency (TEN noise was presented at 60 dB HL) (Moore et al., 2004). Thus, masked thresholds demonstrated greatest variability at 4000 Hz compared to the other frequencies of the TEN(HL) test; however, the authors noted that performance for these normal hearing individuals was never higher than +6 dB SNR and therefore considered within "normal" limits by the TEN test criteria.

In the current study, both groups demonstrated significantly better SNRs at this frequency (4000 Hz) compared to the other test frequencies. The Moore et al. (2004) study did not provide any statistical analysis of masked threshold performance across test frequency. Therefore, the pattern of possible differences in SNR performance at different test frequencies cannot be compared directly between the two studies. The significantly lower (better) SNRs demonstrated at 4000 Hz compared to other test frequencies for both groups (also between 500 Hz and other test frequencies for the younger group) in the current study are within the range of SNRs demonstrated at these frequencies in the Moore et al. (2004) study. Consequently, while the current study demonstrated significant differences in SNRs between test frequencies on the TEN (HL) test, the mean values of the SNRs observed in the current study are similar (or within the range) to previous findings (Moore et al., 2004) across test frequencies considered to be within "normal" limits for the TEN(HL) test criteria.

The slight variation in mean SNRs observed across frequencies for the current study and the study by Moore et al. (2004) may be due to the use of different earphones. The current study used insert earphones (ER-3A) and the Moore et al. (2004) study used

TDH-50 earphones. At least one report indicates that there is more variability in thresholds measured with TDH-49 and TDH-50 earphones than with TDH-39 earphones, which have a comparable frequency response to the ER-3A insert earphones used in this study (Barham, Sherwood & Lawton, 2004). The use of these different earphones may have resulted in the slightly different SNR performance observed between the two studies, even though both groups of participants had normal to near- normal hearing.

The original TEN noise (TEN (SPL) version) did not account for the non-flat frequency response of different earphones at the eardrum (Moore, 2004). In the TEN (HL) version, the non-flat frequency response of different earphones was considered in formulating the final version of the noise with calibration in dB HL. Many earphones used in clinical practice have frequency responses in which the low and high frequencies roll off (decrease) rapidly (Moore, 2004). Therefore, the specific SNR measures at each test frequency may vary slightly depending on the type of earphone used. When adjusting for this difference in frequency response, the TEN (HL) test applied different “correction factors” (decreasing or increasing the noise) at different frequencies. The authors derived these “correction factors” in part based on the Reference Equivalent Threshold Sound Pressure Levels (RETSPLs) for the TDH-39, TDH-49, and TDH-50 earphones (Moore et al., 2004). The current study utilized insert earphones (ER-3A) because they aid in preventing collapsing ear canals which is prevalent in the elderly population (Randolph & Schow, 1983). Insert earphones have a relatively flat frequency response for the frequencies tested by the TEN (HL) test (500-4000 Hz). Although the TEN (HL) test was intended to be used with any audiometer and earphone routinely used in clinical audiology, it may be that slight variations in SNRs could be observed due to different earphones used. These slight variations may be greater at the lowest (500 Hz) and highest (4000 Hz) frequencies tested by the TEN (HL) test depending on the earphone's frequency response. In the current study, the greatest difference in SNR performance and best (lowest) SNR performance was observed at 4000 Hz for both groups (better performance was also seen at other low frequencies for the younger group). It is notable that these are the most remote frequencies tested on the TEN test, such that variation in output level of the broadband noise at the extremes of the spectrum due to varying earphone frequency responses would most likely affect these frequencies. Although the differences in SNR were significant at these frequencies compared to the mid-frequencies, the magnitude of the mean SNR difference was within 1-2 dB. Therefore, these significantly better SNRs at these frequencies may have relatively minor clinical relevance.

Effect of Trial

A significant main effect of trial was found in the current study, revealing that all participants performed better (lower SNRs) on trial two (M=-2.0556) compared to trial one (M=-1.6905). This finding suggests that there was a learning effect demonstrated by all participants that allowed them to perform better (lower SNRs) when tested on the second trial. While this finding was statistically significant, the actual mean difference in SNR from the first trial to the second trial was 0.37 dB. Therefore the average SNR improvement of all participants was not even 1 dB SNR from trial one to trial two. The final step size for determining threshold on the TEN (HL) test is 2 dB, therefore this mean difference is not even the difference of a single step size.

Other studies have evaluated the repeatability of the TEN test (Cairns et al., 2007; Munro et al., 2005) and found that it has good test-retest reliability. Some differences between these studies and the current study were the time intervals between test administration, the age of the participants, and the degree of hearing loss. In the study by Munro et al. (2005), the participants were teenagers (aged 12-18 years, mean age = 14 years) with long-standing severe-to-profound sensorineural hearing loss, who were evaluated on two occasions, 12 months apart. The audiometric thresholds revealed good repeatability (mean difference between tests of approximately 0 dB) and 90% of the re-test values were within 10 dB of the initial values of the TEN (SPL) test. Of 24 ears that could be classified into an actual category (dead region, or no dead region), only two ears (7.1%) changed category (Munro et al., 2005). Therefore the authors deemed the TEN (SPL) test to demonstrate good repeatability for this clinical population.

In order to assess the repeatability of the TEN (HL) test, Cairns et al. (2007) used the new version of the test, an ascending step size of 2 dB and a smaller time interval between test administration (less than five days). Participants were teenagers with sensorineural hearing loss and adults with high-frequency sensorineural hearing loss. The difference in mean thresholds between trials was less than 1 dB across test frequencies for both groups, which was not statistically different for either group (Cairns et al., 2007).

For the older group in the Cairns et al. (2007) study, SNRs were lower on the second test administration compared to the first, but the overall mean difference was only 0.63 dB (Cairns et al., 2007). This finding is similar to the findings of the current study, which found an overall mean difference of 0.37 dB between trials. Although this difference was significant in the current study, the magnitude of the difference is less than 1 dB. Because the TEN (HL) test employs behavioral measures, variations in threshold measurement from one test session to the next would be expected due to individual variability. These changes may be influenced by the participant's concentration, motivation, criteria for responding on that day, etc. (Cairns et al., 2007). While a significant difference between trials was found in the current study, the small magnitude of this difference, suggests that the TEN (HL) test has good repeatability for clinical use, at least within the time period assessed.

Clinical Implications

The TEN (HL) test (Moore et al., 2004) was designed to be used as a clinical measure to assess quickly whether individuals have a cochlear dead region or not. Because dead regions are expected in individuals with sensorineural hearing losses greater than 55-60 dB HL due to the IHC damage and/or loss (Ruggero et al., 1997; Yates, 1990), the test is not designed to be used on every clinic patient. Clinic patients with this degree of sensorineural hearing loss vary in age, but it is common to see older individuals with varying degrees of sensorineural hearing loss in a typical clinical population. Therefore, it can be presumed that the TEN (HL) test may be the measure of choice to determine if an older, hearing-impaired individual has a cochlear dead region. The current study found significant differences in the performance of younger and older individuals with normal to near-normal hearing sensitivity on the TEN (HL) test, which raises the possibility that age influences performance on this test. Because the norms for the TEN (HL) test are based on the performance of young to middle-aged listeners, it is possible that older hearing-impaired listeners may be more likely to exhibit dead regions because of the combined effects of age and hearing loss. However, the mean SNRs measured for both the younger and older groups (both with normal to near-normal hearing) in the current study ranged from -3 dB SNR to almost +3 dB SNR (see Figure 3). Although there were significant differences between the two groups, overall the TEN (HL) test yielded accurate results in classifying all of these individuals with normal to near-normal hearing (hearing sensitivity not indicative of a dead region) as not having a dead region (+10 dB or more SNRs).

When considering individuals with sensorineural hearing loss, this age difference may have a greater impact. Previous studies have found that SNRs are typically 2-3 dB higher (poorer) for individuals with hearing loss compared to normal hearing individuals (Glasberg & Moore, 1986). This difference has been attributed to loss of frequency selectivity caused by broader auditory filters observed in individuals with sensorineural hearing loss. Therefore, it is expected that individuals with sensorineural hearing loss who do not have dead regions will demonstrate masked thresholds (SNRs) that are approximately 2-3 dB higher (poorer) than those of normal hearing listeners in the TEN noise (Moore et al., 2000). When the original criteria or “rule” for determining a dead region was formulated, this slightly higher SNR (2-3 dB) for individuals with sensorineural hearing loss but no dead regions was determined to be considerably lower (better) than the +10 dB (or higher) SNR observed for individuals with dead regions (Moore et al., 2000). However, these criteria do not account for differences in SNR observed due to aging effects.

When adding the 2-3 dB higher SNR due to hearing loss to the +3 dB SNR observed as the maximum value in the current study, an older individual with sensorineural hearing loss and no dead region may demonstrate SNRs as great as +6 dB in the TEN noise. While the current study found +3 dB SNR as the maximum SNR for a group of normal to near-normal hearing older individuals, Gifford and Bacon (2005) found a 9 dB higher SNR for older individuals compared to younger individuals when utilizing a different masking noise (Gifford & Bacon, 2005). In theory, SNRs for individuals with hearing loss (+2 to +3 dB SNR) added to SNRs for older individuals with normal hearing (+3 to + 9 dB SNR) could demonstrate SNRs of up to +12 dB on the TEN (HL) test simply due to hearing loss and age-related deficits. This would result in misclassification of a dead region in older hearing-impaired individuals with sensorineural hearing loss, if the currently recommended 10 dB shift criterion for a dead region is employed.

Preminger et al. (2005) utilized a stricter criterion for determining a dead region. This study employed a 15 dB masked threshold above the level of TEN noise (or + 15 dB SNR) to classify a dead region. If this stricter criterion was recommended for use with the TEN (HL) test, it would theoretically allow for differences in SNRs that could be attributed to hearing sensitivity and age. However, by employing a more conservative criterion the TEN (HL) test might not be as sensitive in identifying dead regions. Further, the study by Preminger et al. (2005) utilized the TEN (SPL) version of the test. Therefore, future studies may be warranted to investigate whether or not a stricter SNR criterion is more accurate for diagnosing dead regions in older hearing-impaired listeners compared to the current recommendations of a +10 dB or greater SNR on the TEN (HL) test (Moore et al., 2000; Moore et al., 2004). Validation of these results with another measure, such as PTCs, would assure that the new criterion continued to be sensitive in identifying dead regions.

The current study supports previous findings (Moore et al., 2000; Moore et al., 2004) in that individuals with normal to near-normal hearing were not diagnosed as having dead regions by the TEN test (SNRs less than 10 dB). Although the current study reported significant differences in the SNR performance of younger and older listeners with similar hearing sensitivity on the TEN (HL) test, clinically these findings would still allow for accurate diagnosis of no dead region.

The current study found differences in SNR performance for the two groups at different test frequencies. The younger group had better (lower) SNRs at the lowest (500 Hz) and highest (4000 Hz) frequencies compared to the mid-frequencies, while the older group demonstrated better (lower) SNRs at 4000 Hz compared to all other frequencies. These differences were statistically significant. However, the actual mean SNR values in the current study do not differ from the "normative" SNR data across frequency provided by Moore et al. (2004) for performance of normal to near-normal hearing listeners on the TEN (HL) test. The older group's mean SNR performance across test frequency in the current study ranged from +.15 to +1.4 dB from 500 to 3000 Hz and was -.56 dB at 4000 Hz. The mean SNR value reported by Moore et al. (2004) ranged from -.70 dB to +.10 dB from 500 to 3000 Hz and was -.50 dB at 4000 Hz. Therefore, the greatest mean SNR difference between the two studies (current study and Moore et al., 2004) was approximately 1 dB. The younger group in the current study demonstrated mean SNRs consistently better (lower) (ranging from -2.2 to -3.2 dB) across frequencies compared to the young-to-middle-aged group in the Moore et al. (2004) study. This may be due to methodological differences between studies, including age range of the younger groups and earphones used.

Therefore, while there were significant differences found between the two age groups at different TEN noise levels and different frequencies in the current study, these differences were not large enough to classify any of these normal hearing listeners (younger or older) to be misdiagnosed by the TEN (HL) test. However, the poorer overall SNR performance of the older listeners suggests that new criteria for the diagnosis of a dead region may be warranted, particularly for older individuals with hearing loss because the poorer SNR attributed to age is likely to be additive to the poorer SNR attributed to hearing loss, resulting in misdiagnosis. A future study that evaluates older individuals with hearing loss on the TEN (HL) test and perhaps utilizes a more established measure (like PTCs) to corroborate the findings may be needed.

Currently, data suggesting useful hearing aid treatment options for individuals identified as having dead regions by the TEN test are limited. Research conducted by Vickers et al. (2001) and Baer et al. (2002) on individuals determined to have high-frequency cochlear dead regions suggested that amplification beyond 1.7-2 times the edge frequency of the dead region provides no additional benefit (Baer et al., 2002; Moore, 2004; Vickers et al., 2001). Transpositional hearing aids (hearing aids that send the information that would normally be conveyed to the dead region to an area with intact auditory function instead) have been offered as a possible solution for individuals diagnosed with dead regions (Moore et al., 2000; Vickers et al., 2001); however these instruments have not been well received as they currently have not demonstrated significant benefit. This lack of benefit resulting from “shifted” information has been demonstrated in research conducted with normal hearing and cochlear implant listeners (Shannon, Galvin, & Baskent, 2001). In this study, “holes” in the tonotopic representation of the cochlea revealed that remapping the information typically found in the hole to either the apical side of the hole, the basal side of the hole, or splitting the information to both sides of the hole showed no improvement in speech recognition performance for either group. In fact, the normal hearing group demonstrated the same benefit when the information was presented at the edge boundaries of the hole as when the information was dropped altogether (Shannon et al., 2001). Additional research is needed to evaluate if remapping this information from regions that are no longer functioning to regions with intact auditory function can be conducted with more successful outcomes.

Limitations and Future Directions

In the current study, both groups of participants demonstrated normal to near-normal hearing sensitivity that was defined as pure-tone thresholds $\leq$ 30 dB HL from 250-8000 Hz. Hearing thresholds of 16-30 dB HL are clinically classified as slight-to-mild hearing losses. These criteria were considered normal to near-normal for the current study because dead regions are associated with greater degrees of hearing loss (IHC damage and/or loss is associated with hearing loss of 55 to 60 dB HL). However, these somewhat lax criteria allowed for the two groups of participants to have some variability in “normal” hearing sensitivity. Indeed, pure-tone thresholds were significantly different between groups, indicating that the younger group had slightly better hearing sensitivity than the older group. It is possible that this difference in hearing sensitivity could account for some of the differences observed between the two groups’ actual SNR performance. Future studies should attempt to match the two age groups more closely based on hearing sensitivity across frequency. In this way, any differences in SNR performance between the two groups would be attributed exclusively to age differences.

This study only included participants with normal hearing sensitivity. However, the TEN (HL) test is intended to be used with individuals with sensorineural hearing loss for the identification of dead regions. Future studies should consider including older and younger individuals with sensorineural hearing loss as well as those with normal hearing sensitivity. This would allow for comparisons of the effects of age and hearing sensitivity on measured SNR on the TEN test. Also, if poorer (higher) SNR performance is observed for older listeners with normal hearing and with hearing loss, these results may provide further evidence that new normative data for older adults are needed, and may also suggest appropriate normative values for older individuals with different pure-tone thresholds. A limitation in the current study is that although a significant age difference in SNR performance was demonstrated, the application of these results to older adults with sensorineural hearing loss is somewhat speculative at present.

Another limitation of the current study was the limited mean age of the older participants. The mean age of the older group was 66.7 years of age, which is fairly young for an older group. The criteria for the study included individuals between the ages of 61 to 81 years of age. However, it was difficult to find older individuals with normal to near-normal hearing sensitivity in this age range. The oldest individual in the current study was 76 years of age. Only four out of the 18 older individuals (20%) were in their 70s and no individual in the current study was between 80-81 years of age. Future studies should attempt to recruit individuals in older decades to investigate whether age differences are observed in these individuals and to examine the magnitude of these differences by age decade. If age differences are demonstrated, new criteria for the TEN (HL) test may be warranted that are specific for these different age decades. Further, future studies should attempt to include a greater number of participants to ensure that the findings truly generalize to a “typical” clinical population. The current study had a limited number of participants in each group (n =18 per group), resulting in a total of only 36 participants.

Finally, the current study utilized insert earphones (ER-3A). The TEN (HL) test was evaluated on normal to near-normal hearing listeners using TDH-50 earphones. The frequency response of these earphones differs slightly and could influence results. The TEN (HL) noise was altered to account for the non-flat frequency response of the TDH-39, TDH-49, and TDH-50 earphones. Therefore, a direct comparison of performance with these TDH earphones and insert earphones would be useful to observe if slight variations in SNR are found.

Chapter 7: Summary and Conclusions

The purpose of this study was to investigate the effects of age on the TEN (HL) test, and to determine if the normative data obtained from younger and middle-aged listeners are appropriate for older listeners. The principal findings were:

1) Older normal to near-normal hearing adults demonstrated significantly poorer (higher) SNRs on the TEN (HL) test than younger normal to near-normal hearing adults at all three TEN noise levels (40, 60, and 80 dB HL) and all seven test frequencies (500, 750, 1000, 1500, 2000, 3000, 4000 Hz).
2) The greatest difference between groups was observed for the highest level of TEN noise (80 dB HL). The greatest difference in SNRs was at 4000 Hz compared to the other test frequencies for both groups. Both groups demonstrated significantly better (lower) SNRs at this frequency compared to other test frequencies. The younger group also demonstrated better (lower) SNRs at 500 Hz compared to two other test frequencies.
3) A significant main effect of trial was found in the current study, revealing that all participants performed better (lower SNRs) on the second trial compared to the first. While this finding was statistically significant, the magnitude of this improvement from Trial 1 to Trial 2 (0.37 dB) was not even a single step size (2 dB). Therefore, the TEN (HL) test was found to have good repeatability for clinical use in the current study, at least within the time period assessed.

Although the current study found significantly different SNR results between the two groups at all TEN noise levels and at all test frequencies evaluated, the mean SNR values for both groups were still considered within normal limits at all noise levels and test frequencies using the +10 dB SNR or greater criterion for diagnosing a dead region. The greatest mean SNR observed in the current study was +3dB SNR (older group). This SNR value is clearly lower than the SNR required for a dead region.

However, this mean +3 dB SNR demonstrated for the older group was significantly higher than that observed for the younger group. Combining this age-related difference in TEN (HL) SNRs with the expected difference in SNRs associated with hearing loss suggests that older individuals with sensorineural hearing loss may demonstrate SNRs as great as +5 to +12 dB higher than younger individuals due to the combined effects of aging and hearing loss. This difference may influence the diagnosis of a dead region in an older hearing-impaired individual. No previous study has investigated whether age differences on the TEN (HL) test exist due to TEN noise level or test frequency. Future studies that include younger and older individuals with normal hearing and sensorineural hearing loss are needed to assess these differences further and examine whether a different criterion (such as a +15 dB SNR shift) is warranted with this population.

Appendix A – Case History

Participant: ___________ Test Date: ___________

Case History:

1. What is your age? ________
2. To the best of your knowledge, please check off if you have or have had any of the following:
    a. Hearing Loss ____
    b. A history of ear infections or middle ear pathology ____
    c. A history of ear surgery ____
    d. Problems with sound tolerance (hyperacusis) _____
    e. History of being exposed to loud/excessive noises ____
        i. If answered yes, please specify what noise and how long exposed ____

THE SHORT PORTABLE MENTAL STATUS QUESTIONNAIRE (SPMSQ)

Question	Response	Incorrect Responses
1. What are the date, month, and year?		
2. What is the day of the week?		
3. What is the name of this place?		
4. What is your phone number?		
5. How old are you?		
6. When were you born?		
7. Who is the current president?		
8. Who was the president before him?		
9. What was your mother's maiden name?		
10. Can you count backward from 20 by 3's?		

SCORING:*

0-2 errors: normal mental functioning
3-4 errors: mild cognitive impairment
5-7 errors: moderate cognitive impairment
8 or more errors: severe cognitive impairment

*One more error is allowed in the scoring if a patient has had a grade school education or less.
*One less error is allowed if the patient has had education beyond the high school level.
Source: Pfeiffer, E. (1975). A short portable mental status questionnaire for the assessment of organic brain deficit in elderly patients. Journal of American Geriatrics Society. 23, 433-41.
Compiled by the Great Plains Area Chapter of the Alzheimer's Association, 1999.

Appendix C – Flyer

Age-related Effects on the Threshold Equalizing Noise (TEN) Test.

WHAT? The purpose of this research is to determine if there are age related differences on the Threshold Equalizing Noise (TEN) test. This is a test of hearing ability in noise.

Who? Female and male adults between the ages of 18-38 and 61-81 with no known hearing loss, no sensitivity to loud sounds, no ear problems and/or ear surgeries, who are native speakers of English.

How? The study will consist of one 1 ½ to 2 hour test session. You will be asked to complete two brief questionnaires and receive a **FREE HEARING TEST**. Those participants who qualify for the experimental measure will be asked to press a button in response to different tones presented to their ear through an earphone in quiet and in noise conditions.

For more information please contact:

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Appendix D – Website Posting

Age-related effects on the Threshold Equalizing Noise (TEN) test.

Purpose: The purpose of this research is to determine if there are age related differences on the Threshold Equalizing Noise (TEN) test. This is a test of hearing ability in noise.

Eligibility: Female and male adults between the ages of 18-38 and 61-81 with no known hearing loss, no sensitivity to loud sounds, no ear problems and/or ear surgeries, who are native speakers of English.

The study will consist of one 1 ½ to 2 hour test session. You will be asked to complete two brief questionnaires and receive a **FREE HEARING TEST**. Those participants who qualify for the experimental measure will be asked to press a button in response to different tones presented to their ear through an earphone in quiet and in noise conditions.

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Initials_______ Date ______

CONSENT FORM

Project Title	*Age-related effects on the Threshold Equalizing Noise (TEN) test.*
Why is this research being done?	*This is a research project being conducted by Dr. Sandra Gordon-Salant and Christine Gmitter at the University of Maryland, College Park. We are inviting you to participate in this research project because you are an adult ranging in age from 18 to 38 years or from 61 to 81 years of age with no known hearing loss, history of middle ear pathology or surgery, sound tolerance problems (hyperacusis) or auditory processing disorders.* *The purpose of this research project is to determine if the age of the listener has an effect on the amount of threshold shift observed when using the TEN (HL) test, a test of hearing ability in noise. A second goal of this research is to consider if the level of the TEN noise employed has a differential effect for older versus younger listeners on the amount of threshold shift observed.*
What will I be asked to do?	*The procedures involve one test session that will last for approximately 1 ½ to 2 hours. You will be asked to fill out a case history questionnaire and participate in a diagnostic audiometric evaluation to verify that you qualify for the study. During this evaluation you will be seated in a sound booth and asked to repeat back words being presented to each ear through an insert earphone. You will also be asked to press a button every time you hear a beep, or tone, presented to each ear through these same earphones. Then you will be asked to sit quietly and listen while a series of loud tones are presented to both ears through soft ear tips. You may feel a slight pressure change in your ears during this test. If you are a candidate for this study, based on your audiometric results and answers on the case history, you will be asked to participate in the study. During the study, you will be seated in a sound booth and asked to listen to different tones being presented to one ear through an insert earphone. Sometimes the tones will be presented in quiet and sometimes in noise. You will be asked to respond to the various stimuli by pressing a button when you hear the tones.*

Initials ______Date ______

Project Title	*Age-related effects on the Threshold Equalizing Noise (TEN) test.*
What about confidentiality?	*We will do our best to keep your personal information confidential. To help protect your confidentiality, all information collected in this study is confidential to the extent permitted by law. The data provided will be grouped with data others provide for reporting and presentation. All data will be coded by the participant's identification number. If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.*
What are the risks of this research?	*There are no known risks associated with participating in this research project. The sound presentation levels employed will not be harmful to the participants' hearing sensitivity.*
What are the benefits of this research?	*This research is not designed to help you personally, but the results may help the investigator learn more about the effect of age on a new hearing test in noise [TEN (HL) test].*
Do I have to be in this research? **May I stop participating at any time?**	*Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.*
Is any medical treatment available if I am injured?	*The University of Maryland does not provide any medical, hospitalization or other insurance for participants in this research study, nor will the University of Maryland provide any medical treatment or compensation for any injury sustained as a result of participation in this research study, except as required by law.*

Initials ______Date ______

What if I have questions?	*This research is being conducted by Dr. Sandra Gordon-Salant and Christine Gmitter in the Department of Hearing and Speech Sciences at the University of Maryland, College Park. If you have any questions about the research study itself, please contact* ***Dr. Sandra Gordon-Salant at:*** ***Department of Hearing and Speech Sciences*** ***0100 LeFrak Hall*** ***University of Maryland-College Park*** ***College Park, MD*** ***Telephone number: 301-405-4225*** ***Email: SGORDON@hesp.umd.edu*** ***Christine Gmitter (Student Investigator)*** ***Department of Hearing and Speech Sciences*** ***0100 LeFrak Hall*** ***University of Maryland-College Park*** ***College Park, MD*** ***Telephone number: 301-233-6382*** ***Email: cgmitter@hesp.umd.edu*** *If you have questions about your rights as a research subject or wish to report a research-related injury, please contact:* **Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742;** **(e-mail) irb@deans.umd.edu; (telephone) 301-405-0678** *This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.*	
Statement of Age of Subject and Consent	*Your signature indicates that:* *you are at least 18 years of age;,* *the research has been explained to you;* *your questions have been fully answered; and* *you freely and voluntarily choose to participate in this research project.*	
Signature and Date	**NAME OF SUBJECT**	
	SIGNATURE OF SUBJECT	
	DATE	

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