THE IMPACT OF DIRECTIONAL LISTENING ON PERCEIVED LOCALIZATION ABILITY

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An important purpose of hearing is to aid communication. Because hearing-in-noise is of primary importance to individuals who seek remediation for hearing impairment, it has been the primary objective of advances in technology. Directional microphone technology is the most promising way to address this problem. Another important role of hearing is localization, allowing one to sense one's environment and feel safe and secure. The properties of the listening environment that are altered with directional microphone technology have the potential to significantly impair localization ability. The purpose of this investigation was to determine the impact of listening with directional microphone technology on individuals' self-perceived level of localization disability and concurrent handicap.

Participants included 57 unaided subjects, later randomly assigned to participate in one of three aided groups of 19 individuals each, who used omni-directional microphone only amplification, directional microphone only amplification, or toggle-switch equipped hearing aids that allowed user discretion over the directional microphone properties of the instruments. Comparisons were made between the unaided group responses and those of the subjects after having worn amplification for three months. Additionally, comparisons between the directional microphone only group responses and each of the other two aided groups' responses were made.

No significant differences were found. Hearing aids with omni-directional microphones, directional-only microphones, and those that are equipped with a toggle-switch, neither increased nor decreased the self-perceived level of ability to tell the location of sound or the level of withdrawal from situations where localization ability was a factor. Concurrently, directional-microphone only technology did not significantly worsen or improve these factors as compared to the other two microphone configurations. Future research should include objective measures of localization ability using the same paradigm employed herein. If the use of directional microphone technology has an objective impact on localization, clinicians might be advised to counsel their patients to be careful moving in their environment even though they do not perceive a problem with localization. If ultimately no significant differences in either objective or subjective measures are found, then concern over decreases in quality of life and safety with directional microphone use need no longer be considered.

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PREFACE

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1. INTRODUCTION

Human beings use their sense of hearing for two purposes. One purpose is to help with sensing one's environment. Identifying the physical origin of a sound (localization) plays an important role in accurately navigating the environment and feeling safe and secure. Hearing also plays an important role in communication. Our communication settings are constantly changing as we find ourselves trying to attend to signals in a background of other sounds in the environment. Effectively hearing speech in the presence of other sounds is occasionally a challenge for individuals with normal hearing and is one of the biggest obstacles facing individuals with hearing impairment. Difficulty hearing in noise is the chief complaint of individuals with hearing impairment (Cord, Surr, Walden, & Drylund, 2002; Dhar, Humes, Calandruccio, Barlow, & Hipskind, 2004; Jenstad, Seewald, cornelisse, & Shantz, 1999; Kochkin, 1993; Ricketts & Dhar, 1999; Schum, 2000; Smriga, 2000; Voll, 2000; Young, Goodman, & Carhart, 1980).

An explanation for the increased challenge of effectively hearing speech in noise among those with sensory hearing impairment is twofold. Reduced psychoacoustic abilities, beyond reduced sensitivity, are present in most cases of hearing loss. It is the combination of these reduced psychoacoustic abilities with the ever changing listening environment that causes individuals with sensory impairment to struggle with effectively communicating in noisy environments.

Because ameliorating the problem of hearing in noise is of primary importance to individuals with hearing impairment, it has been the primary objective of technological advances in amplification for several decades. Efforts have been made to develop circuitry that theoretically helps to reduce the effects of background noise with hearing aids. While theoretically sound, the promise of many of these "noise-reduction" circuits has not been realized in practice (Levitt, Neuman, Mills, & Schwander, 1986; Levitt et al., 1993; Schwander & Levitt, 1987; Stein & Dempesy-Hart, 1984; Weiss, 1987). The directional microphone is designed in such a way that it is more sensitive to sounds coming from one location (typically, in front of the listener) than from other locations and in this way improves the signal-to-noise ratio.

Research in the area of directional microphone technology has consistently produced reports of improved understanding of speech in noise in the laboratory setting (Agnew, 1997; Agnew & Block, 1997; Boymans & Dreschler, 2000; Chasin, 1994; Christensen, 2000; Hillman, 1981; Killion, 1997b; Mueller, 1981; Mueller, Grimes, & Erdman, 1993; Mueller & Johnson, 1979; Nielsen, 1973; Preves, Sammeth, & Wynne, 1999; Pumford, Seewald, Scollie, & Jenstad, 2000; Ricketts & Dhar, 1999; Sung, Sung, & Angelelli, 1975; Valente, Fabry, & Potts, 1995; Voss, 1997; Wouters, Litiere, & van Wieringen, 1999). This type of technology appears to be the most promising way to address the speech-in-noise issue. However, the extent to which this advantage is realized in the real world is less clear. Some studies suggest that the directional benefit derived in real world listening situations is less than might be expected based on the benefit observed in the laboratory (Boymans & Dreschler, 2000; Cord et al., 2002; Cord, Surr, Walden, & Drylund, 2004; Nielsen, 1973; Preves et al., 1999; Surr, Walden, Cord, & Olson, 2002; Valente et al., 1995; Walden, Surr, Cord, & Drylund, 2004). Various explanations for this discrepancy exist and among the most prominent are that laboratory measures of speech recognition in noise may overestimate the practical benefits of directional microphones (Amlani, 2001) or that some nuance of the complex interaction of the acoustic factors of the real world environment is the cause (Dhar et al., 2004).

It is optimal in rehabilitation to consider all aspects of the individual when choosing a course of treatment. This should involve not only examining the nuances of the disability itself, and the best remediation for the disability based on those nuances, but also the psychological impact both of having the disability and of the subsequent course of treatment.

While communicating effectively in noise seems to be of highest priority for individuals with hearing impairment, a second utility of hearing is allowing the listener to sense their environment for safety and security. There is evidence to support the notion that localizing is important to individuals with hearing impairment (Eriksson-Mangold, Hallberg, Ringdahl, & Erlandsson, 1992). Noble, Ter-Horst, and Byrne (1995) showed that self-assessed disability associated with a decreased ability to localize was significantly associated with feelings of confusion and loss of concentration.

Researchers have found that hearing aids can disturb sound localization ability (Byrne, Noble, & Lepage, 1992; Noble & Byrne, 1990; Noble, Sinclair, & Byrne, 1998). The impact of listening in a directionally enhanced environment on the individual's ability to localize is unclear. The very properties of directional microphone technology that promote enhanced performance in noise may create problems in localization. The listener may be left unable to detect signals from much of the complex, real-world acoustic environment. The impact that this aspect of enhanced directional hearing might have on activities of daily living has yet to be determined.

The purposes of this investigation were (1) to determine the impact of directional listening on activities of daily living, and feelings of safety and isolation among older individuals with impaired hearing; and (2) to determine if the ability to choose directionally enhanced versus omni-directional amplification, according to the listening situation, eliminates any self-perceived localization disabilities or handicaps among these subjects. The investigation included groups of individuals who 1) did not use amplification, 2) listened in an omni-directional, amplified environment, 3) listened in a directionally enhanced, amplified environment, or 4) had the freedom to choose the directional properties of the amplified environment. Following are the specific research questions that were addressed:

Does a significant difference exist between the self-perceived localization disabilities and/or handicaps of;

1. A group of unaided individuals and that same group after listening in an omni-directional, amplified environment?

2. A group of unaided individuals and that same group after listening in a directionally enhanced, amplified environment?

3. A group of unaided individuals and that same group after wearing toggle-switch equipped hearing aids where the user has the freedom to choose the directional microphone properties of the amplified environment?

4. A group that listens in an omni-directional, amplified environment versus a group that listens in a directionally enhanced, amplified environment?

5. A group that listens in a directionally enhanced, amplified environment versus a group that has the freedom to choose the directional microphone properties of the amplified environment?

Hypotheses included:

1. The unaided group would have more self-perceived disabilities and handicaps associated with localization impairment than each of the amplified groups.

2. Being forced into directional listening at all times would cause greater problems with localization and as such this group was expected to have more self-perceived disabilities and handicaps associated with localization impairment than the group listening in an omni-directional, amplified environment.

3. The flexibility associated with being able to choose the directional setting of the listening environment, based on the communication setting, would eliminate any self-assessed localization disabilities and handicaps evidenced by individuals who listened only in a directionally enhanced, amplified environment.

The next section will provide a literature review of the topics introduced herein. An overview of the psychoacoustic properties of sensory hearing loss, hearing aid circuit options designed to combat the speech-in-noise problem and their limitations, the psychological impact of disability and its relationship to successful rehabilitation, and a rationale for the proposed course of study will be provided.

2. LITERATURE REVIEW

2.1. REDUCED PSYCHOACOUSTIC ABILITIES

Patuzzi, Yates, and Johnstone (1989) provide a model for hearing that suggests that in the normal cochlea the outer hair cells (OHCs) increase the amplitude of basilar membrane vibration at the place on the membrane that corresponds to the frequency of the sound. A hearing loss of cochlear origin with air conduction thresholds less than 60 dB HL is consistent with damage to the OHCs (Faulkner, Rosen, & Moore, 1990; Rosen, Faulkner, & Smith, 1990). Hearing losses greater than 60 dB HL involve destruction of the inner hair cells (IHCs) and disruption of afferent function, in addition to the loss of the OHCs function. The loss in sensory function can produce greatly reduced psychoacoustic abilities (Faulkner et al., 1990; Rosen et al., 1990).

For this reason, sensory hearing impairment cannot solely be defined as a loss of audibility as it often is comprised of loss of some of these psychoacoustic functions as well. Among the characteristics of sensory hearing loss are loudness recruitment (Huizing, 1948; Van Tasell, 1993; Villchur, 1974; Yates, 1990), difficulties with temporal resolution (Buus & Florentine, 1985; Fitzgibbons & Wightman, 1982; Glasberg, Moore, & Bacon, 1987; Irwin, Hinchcliffe, & Kemp, 1981; Tyler, Summerfield, Wood, & Fernandes, 1982; Van Tassell, 1993), reduced frequency selectivity (Bonding, 1979; Carney & Nelson, 1983; Dallos & Harris, 1978; Dreschler & Plomp, 1980; Evans, 1975, 1978; Festen & Plomp, 1983; Florentine, Buus, Scharf, & Zwicker, 1980; Hoekstra & Ritsma, 1977; Leshowitz & Lindstrom, 1977; Stelmachowicz, Jesteadt, Gorga, & Mott, 1985; Wightman, McGee, & Kramer, 1977; Zwicker & Schorn, 1978), reduced speech perception in noise (Killion, 1997a, 1997b, 1997c; Pearsons, Bennett, & Fidell, 1976; Plomp, 1977; Roberts & Schulein, 1997), and problems of sound localization (Batteau, 1967, 1968; Fisher and Freedman, 1968; Groen, 1969; Kuhn & Guernsey, 1983; Noble et al., 1995; Noble, Byrne, & Ter-Horst, 1997; Noble, et al., 1998; Saberi, Dostal, Sadralobadai, Bull, & Perrott, 1991; Tonning, 1975).

2.1.1. Loudness Recruitment

The loss of hearing sensitivity corresponds to a reduction in the dynamic range of hearing from an individual's threshold of audibility to their uncomfortable loudness level (UCL). The consequence is loudness recruitment. Yates (1990) offers a physiological explanation for this phenomenon. He notes that the input/output (I/O) function of the healthy cochlea is non-linear at low intensity levels, but linear at higher intensity levels. If we assume that loudness is proportional to basilar membrane displacement, then at low stimulation levels, a cochlea without the benefit of the OHC amplifying system will require a higher input level to achieve the same membrane displacement as a normally functioning cochlea. Whereas high stimulus levels will produce the same basilar membrane displacement and therefore the same loudness as produced by the normally functioning cochlea (Van Tasell, 1993). It has been suggested (Huizing, 1948; Villchur, 1974) that by distorting the subject's perception of amplitude relationships among the acoustical elements of speech, recruitment is a sufficient cause for loss of speech intelligibility, especially in noisy environments.

2.1.2. Temporal Resolution

Temporal resolution refers to the capacity to extract and encode temporal features of a stimulus waveform (Fitzgibbons & Wightman, 1982). Gap detection tests measure a listener's ability to detect brief temporal gaps that separate two successive stimuli. The duration of the minimum detectable temporal gap in wideband noise is longer for people with hearing impairment than for individuals with normal hearing (Fitzgibbons & Wightman, 1982; Irwin et al., 1981; Tyler et al., 1982). This finding is most likely due to the reduction in hearing sensitivity at high frequencies for these individuals, rather than to any real alteration of the mechanisms responsible for temporal resolution (Van Tasell, 1993). This is evidenced by studies that have shown that the gap detection thresholds of listeners with hearing impairment closely resemble those of normally hearing listeners when high frequency hearing losses are simulated in the latter (Buus & Florentine, 1985). There is some evidence that gap detection thresholds are larger for both individuals with normal and impaired hearing at low sensation levels (Glasberg et al., 1987). An inability to detect the temporal gaps of complex signals (i.e., speech) may cause significant distortion of sounds. Any psychoacoustic distortions of signals will make them more difficult to understand, particularly if the listener is attempting to parse the characteristics of complex sounds and/or more than one sound in combination as in listening to speech in noise.

2.1.3. Frequency Selectivity

Frequency selectivity refers to the ability of the auditory system to separate the frequency components of a complex sound (Florentine et al., 1980, Hoekstra & Ritsma, 1977). Stated differently, frequency selectivity is the ability to hear one frequency in the presence of others (Bonding, 1979). Auditory frequency resolution is impaired in the presence of cochlear hearing loss (Bonding, 1979; Carney & Nelson, 1983; Dallos & Harris, 1978; Festen & Plomp, 1983; Florentine et al., 1980; Hoekstra & Ritsma, 1977; Leshowitz & Lindstrom, 1977; Stelmachowicz et al, 1985; Wightman et al., 1977; Zwicker & Schorn, 1978). Impaired frequency resolution may be responsible for the reduced speech processing capabilities often seen in listeners with hearing impairment (Bonding, 1979; Dreschler & Plomp, 1980; Evans, 1975, 1978; Hoekstra & Ritsma, 1977; Stelmachowicz et al., 1985; Zwicker & Schorn, 1978). Studies that attempt to quantify human frequency selectivity capabilities are numerous and include comparisons of subjects with normal hearing and hearing impairment, critical bandwidth for loudness summation, psychophysical tuning curves (PTCs), and simultaneous- versus forward-masking stimulus paradigms. As a body of literature, these methods demonstrate the psychophysical characteristics of the frequency resolving capabilities of the impaired system and detail the behavioral correlates of these impaired capabilities. Appendix A - Table 1 provides a synopsis of the goals, conclusions, and limitations of many of these studies.

2.1.3.1. Measurement of Frequency Selectivity

One of the oldest measures of frequency selectivity of the ear is the critical bandwidth (CB) for loudness summation (Bonding, 1979). Loudness summation refers to the increase in loudness when bandwidth exceeds the critical band and the overall sound pressure level (SPL) of the signal is held constant (Florentine et al, 1980). Acoustical input is first analyzed into critical bands and then these are summed (Zwicker & Scharf, 1965). For bandwidths exceeding the critical band, the individual components of a complex sound interact less and contribute independently to the overall loudness. For frequency selectivity, this model predicts less loudness summation if the critical band of the frequency is enlarged since fewer bands would be summed. Larger critical bandwidths are frequently a feature of the impaired system as is reduced frequency selectivity (Florentine & Zwicker, 1979; Martin, 1974; Scharf & Hellman, 1966).

Another and currently more popular way of measuring frequency selectivity is by obtaining psychophysical tuning curves (PTCs). The PTC is a sensitive technique with which to obtain a focused view of auditory masking. The effectiveness with which one stimulus masks another is a direct measure of the limits of selectivity; masking will occur when selectivity breaks down (Wightman et al., 1977).

Bonding (1979), tested the hypothesis that frequency selectivity and speech discrimination are correlated for patients with cochlear lesions. The methods examined critical bandwidth for loudness summation, psychophysical tuning curves, and speech discrimination scores. These methods allowed examination of which of the two ways for measuring frequency selectivity is a more valid measure. Correlational analysis revealed that critical bandwidth measures did not correlate well with either the degree of hearing loss or with the subjects' speech discrimination scores. PTCs on the other hand changed with increasing hearing loss, as did speech discrimination scores. Also, a significant correlation was noted between speech discrimination scores and cochlear tuning as expressed by the PTC. Based on these results, Bonding proposed that PTCs are a more valid measure of frequency selectivity than are CBs. In a similar comparison done by Florentine et al., (1980) PTCs more readily revealed reduced frequency selectivity than did measures of loudness summation.

2.1.3.2. Interpretation of Results

PTCs can be used to describe the frequency resolving capabilities of the auditory system. Quantifying the auditory frequency selectivity capabilities of humans is difficult. Several investigators have discussed the necessity of using high-SPLs in order to have signals loud enough to be audible to the individual with hearing impairment. This is of issue for at least two reasons: (1) frequency resolution becomes poorer with increasing signal level (Evans, 1977; Festen & Plomp, 1983; Florentine et al., 1980; Rhode, 1978; Scharf & Meiselman, 1977); and (2) presentation level differs for normal hearing and hearing-impaired listeners when a sensation level (SL) is applied. The subjects with hearing impairment experience a higher SPL.

Investigators in this area argue that any comparison of PTCs from subjects with normal hearing and those with hearing impairment should be done at equal SPLs. Carney and Nelson (1983) suggest that impaired ears may not be quite as poor at resolving high-level stimulation as has been implied. Also, there is evidence that results from PTCs obtained from individuals with normal hearing at high-SPL levels are discontinuous and are the product of the auditory sensation of combination tones (Carney & Nelson, 1983; Festen & Plomp, 1983). These results come from studies that use simultaneous masking paradigms to generate PTCs.

Simultaneous masking paradigms also contribute to the difficulty in interpreting PTCs for quantification of frequency selectivity characteristics. A combination tone is the auditory sensation of a pure tone arising from the simultaneous stimulation of the ear by two other primary tones (Leshowitz & Lindstrom, 1977). Masked thresholds actually may represent the thresholds for the combination tone. One can minimize this problem by using probe tones that are low in intensity (20 dB SL or less) (Wightman et al., 1977). Combination tones are not evident at this level; however, this may preclude testing at equal SPLs for both subjects with normal hearing and those with hearing impairment. Another way to deter combination tones is to use a forward masking paradigm when obtaining PTCs (Festen & Plomp, 1983; Green, Shelton, Picardi, & Hafter, 1981; Wightman et al., 1977).

Bearing in mind the limitations of some of the methods used, some general statements can be made regarding the characteristics of PTCs that can be used to describe the frequency resolving capabilities of the auditory system. PTCs usually are depicted on a graph where the x-axis represents the frequency continuum, and the y-axis represents the intensity of the masker. The resultant picture is a representation of how much masking is needed at various surrounding frequencies to mask the probe tone of a given frequency. Appendix B - Figure 1 is an example of the classic "V"-shaped PTC generally observed in people with normal hearing sensitivity.
In this example, the masker that is closest in frequency to the probe tone is the most efficient masker of that tone. Another aspect of the PTC of individuals with normal sensitivity is a steep high-frequency slope and a shallower low-frequency slope. This is indicative of more efficient masking by maskers below the frequency of the probe tone. There is considerable intra-subject variability for these slopes depending on the probe frequency (Carney & Nelson, 1983).

In general, PTCs for individuals with sensory hearing impairment are broad (Bonding, 1979; Carney & Nelson, 1983; Dreschler & Plomp, 1980; Festen & Plomp, 1983; Florentine et al., 1980). This finding speaks to a decreased ability to separate individual formant frequencies, which can cause an increased susceptibility to noise. The widened auditory filters can be expected to smooth out the auditory representation of spectral peaks and valleys in speech (Bacon & Brandt, 1983; Sidwell & Summerfield, 1985; Van Tasell, Fabry, & Thibodeau, 1987). Noise affects the listener with hearing impairment because he or she is already operating with a reduced redundancy speech signal and the widened filters decrease the auditory contrasts of the signal (Stone & Moore, 1992). These general characteristics of the frequency selectivity of listeners with hearing impairment contribute significantly to distortion of signals and increased discrimination difficulties with complex sounds in noise.

The reduction in psychoacoustic abilities due to sensory hearing loss compounds from one psychoacoustic ability to the next and as a group contributes significantly to the problem of being able to hear speech-in-noise.

2.1.4. Problems with Speech Recognition in Noise

2.1.4.1. Signal-to-Noise Ratio

Our communication settings are constantly changing as we find ourselves trying to attend to signals in a background of other sounds in the environment. Signal-to-noise ratio (SNR) is defined as the sound pressure (typically stated in decibels) of the signal (that which the listener is attending to) minus the sound pressure of any competing sound (background noise). When this value is positive, the signal is louder than the competition; conversely when negative, the noise exceeds the signal. Average speech and noise levels have been measured for several environments. In general the SNR is +5 to +8 dB in public places, 0 dB in transportation vehicles, and approximately +1 dB in a cocktail party environment (Pearsons et al., 1976; Plomp, 1977). A positive SNR should allow one to hear the signal adequately, as it should be audible above the competition. This is true for most individuals with normal hearing sensitivity and for some with specific types of hearing loss (e.g., strictly conductive) as long as the intensity is within the individual's dynamic range. Hearing loss is not always just an issue of sensitivity but often one of selectivity as well. Research has shown that listeners with hearing impairment require 4 to 18 dB enhanced SNR to perform as well on tests of speech perception and recognition than do listeners with normal hearing (Dirks, Morgan, & Dubno, 1982; Killion, 1997a, 1997b; Leshowitz, 1977; Roberts & Schulein, 1997).

2.1.4.2. Evaluating Performance for Speech-in-Noise

Current clinical procedures for measuring speech recognition do not allow an evaluation of performance for communication in background noise conditions. Clinical tests are presented in quiet so as to maximize the potential for obtaining the highest possible speech recognition score. The most common procedure for selecting a presentation level for this type of testing is to test at some constant sensation level (SL) based on pure tone thresholds at typical speech frequencies. Dirks et al., (1982) note that sampling at a constant sound pressure level (SPL) that is based on the individual's pure tone average (PTA) disregards the effects of the absolute SPL of the speech material on the listener's performance. Therefore they suggest testing within the same SPL range for all listeners if the goal is to compare the performance of individuals with normal and impaired hearing. One of the ways that speech recognition performance in noise is commonly measured is with a metric referred to as the critical signal-to-noise ratio. This is defined as the

SNR needed by an individual to achieve a certain predetermined level of performance (typically 50% correct). In the 1982 study, Dirks et al., found that for monosyllable and spondee words individuals with normal hearing require a more positive SNR as the level of the speech increases to achieve the 50% correct criterion. These data corroborate those reported by Leshowitz (1977). Individuals with hearing loss follow suit and require an even more advantageous SNR than that required by those with normal hearing. Additionally, six of twenty hearing-impaired listeners required exceedingly high SNRs and further analysis showed these subjects to be those with the most severe hearing losses (Dirks et al., 1982). These data indicate that a more advantageous listening environment is required when the signal is of higher intensity for the subject to perform equally as well as when the signal was of lower intensity. Individuals with hearing loss consistently listen to higher intensity signals because of the amplification required to make sounds audible. Also, the data suggest that individuals with difficulty listening in noisy conditions will have this difficulty regardless of the type of speech material being attended to (e.g., redundant versus difficult).

Individuals reveal superior performance when listening to speech in noise binaurally as opposed to monaurally. This is especially true when the two signals originate from different directions (Carhart, 1965; Dirks & Wilson, 1969, MacKeith & Coles, 1971). This binaural advantage mainly comes from interaural differences in time and intensity that are caused by the diffraction of the sound waves by the head. Other factors contribute to the diffraction and interaural differences of signals and are discussed, along with findings from evaluations of this binaural advantage for speech in noise, in the following section on localization.

2.1.5. Localization

Another area where the impact of loudness recruitment, and decreased temporal resolution and frequency selectivity is evident is in sound localization. Identifying the location of a sound is important for sensing the environment and feeling safe and secure (Noble et al., 1995). Localization has significance in people's reports of everyday hearing difficulty (Noble et al., 1995). Many variables are involved in localization. The interaction of the sound wave with the physical attributes of the listener and the environment allows for spectral and spatial cues that the individual uses to locate sound. Some physical attributes of the listener that impact localization include; the head (Groen, 1969; Noble et al., 1997), shoulders, torso (Kuhn & Guernsey, 1983; Noble et al., 1998), conchae (Noble et al., 1998), and pinnae (Batteau, 1967, 1968; Fisher & Freedman, 1968; Noble et al., 1997; Noble et al., 1998; Saberi et al.,1991; Tonning, 1975). An individual's ability to freely move their head is important for localization (Di Carlo & Brown, 1961; Freedman & Fisher, 1968; Jongkees & Van Der Veer, 1958; Tonning, 1975; Wallach, 1939, 1940). The medial superior olivary complex of the brainstem is said to be the site at which afferent impulses from the two ears first meet (Nilsson & Liden, 1976). Spectral cues that are used for localization include time/phase differences and/or intensity differences between signals and their echoes.

2.1.5.1. The Precedence Effect

The most frequent way of discussing the use of temporal cues in directional hearing is with a phenomenon known as the precedence effect. This important localization effect illustrates the influence of delay on resulting sound images (Gardner, 1968). Reference to this effect dates back to 1849. It was more clearly defined by an individual named Haas in 1949. For this reason it has been known as the Haas effect. Other names for it have included the law of the first wavefront, auditory-suppression effect, first-arrival effect, threshold of extinction, and limit of perceptibility (Gardner, 1968). For a detailed historical background of the effect see Gardner (1968).

In general, the first signal to arrive at the ears is the primary determinant of the subject's perception of the location of the sound source. Acoustic reflections of the primary source of a sound from the walls, ceilings, etc., will arrive at the ears somewhat delayed. These later arriving sounds are subject to neural suppression. This is the brain's way of minimizing interference with the location of the primary source of the sound. The dominance of the primary signal over these delayed reflections depends on the amount of delay. If the interval is short enough, the listener will perceive only one sound coming from the direction of the primary source. If the interval is sufficiently long, a second sound or echo will be heard.

Litovsky (1997) performed an investigation to determine developmental changes in the precedence effect phenomenon. Reports of developmental studies suggest that the precedence effect is not present at birth and emerges at around 4 – 5 months of age (Clifton, 1985). Young children need longer delays to localize the lagging sound in a dichotic signal than those needed by 5-year old children. Similarly, 5-year old children have longer delays than do adults, but only for complex stimuli (Morrongiello, Kulig, & Clifton, 1984). Minimum audible angle (MAA) refers to the smallest lateral difference in the position of a sound that can be detected reliably. This measure can be obtained for both single source sounds and sounds made up of both a lead and a lag signal. In a study by Morrongiello and colleagues, 5-year old children performed better on tests of MAA than did 18-month olds. Adults performed better than 5-year olds but only on tests of MAA using single source stimuli and not using dichotic signals. These results suggest that localization abilities continue to improve between 18-months and 5-years of age. The results also suggest that basic localization may have reached adult acuity by childhood but precision under conditions where the precedence effect is present has not. Finally, different mechanisms might be responsible for the development of localizing single source versus paired stimuli.

Another cue employed for locating sounds is intensity differences. Sounds that arrive at the ears with more intensity will dominate the perceived location of the sound source. Various manipulations of the environment allow for time/intensity trading. If delayed sounds are sufficiently loud enough they can overcome the influence of the temporal delay.

2.1.5.2. General Use of Cues for Localization

While the specifics vary from study to study, localization in the low-frequency range is based on the ability to detect phase or time differences (Nilsson & Liden, 1976; Wightman & Kistler, 1992; Zwislocki & Feldman, 1956). For high-frequency tones differences in intensity are of greatest importance (Groen, 1969; Nilsson & Liden, 1976; Nordlund, 1962b; Nordlund & Liden, 1963; Sivian & White, 1933; Tonning, 1975; Wightman & Kistler, 1992). These statements have a correlate in physics. The wavelength of an 800 Hz tone is approximately 42 cm in air. This is equal to two times the distance between the ears. For tones with a shorter wavelength or higher frequency, phase differences may correspond with several positions for the source of the sound therefore lending greater weight to intensity cues at frequencies above the 800 Hz cutoff (Kietz, 1957). If an individual suffering from high frequency hearing impairment is unable to hear signals or intensity cues in sounds above 800 Hz, their localization abilities are likely to suffer. Kietz (1957) also noted that the recovery period of the nerve makes instantaneous transference of the neural impulses at higher frequencies impossible. Difference in time becomes important for localizing complex sounds (Nilsson & Liden, 1976). Recall that individuals with hearing impairment also suffer from reduced temporal resolution capabilities. Because an inability to detect the temporal gaps in complex sounds is common among those with impaired hearing, the ability to detect these important timing differences for localizing complex signals also is decreased. Finally, complex sounds are more easily localized than pure tones (Jongkees & Groen, 1946; Nordlund, 1962a, 1964; Tonning, 1975).

2.1.5.3. Spatial Planes and Quadrants

The space surrounding the listener is typically divided into two planes, the horizontal (azimuth) and the vertical (elevation). These planes are further divided into quadrants, the frontal and rearward, and the right and left lateral quadrants. In general, "…the auditory system appears to favor binaural cues over spectral shape cues for azimuth, but must rely on spectral shape cues for elevation" (Middlebrooks & Green, 1991, p. 148). Other investigators (Asano, Suzuki, & Sone, 1990; Mills, 1972; Musicant & Butler, 1984; Weinrich, 1982) support these findings. Noble, Byrne, and Lepage, (1994) investigated the role of hearing loss on various aspects of localization. Some individuals with normal hearing participated and some broad conclusions about the roles of various spatial planes can be made. In general, performance in the frontal horizontal plane (FHP) is more accurate than in the lateral horizontal plane (LHP). Performance in the lateral vertical plane (LVP) is more accurate than for the medial vertical plane (MVP).

2.1.5.4. Contribution of the Physical Attributes of the Listener

The physical attributes of the listener vary the spectrum of the sounds around them. These modifications to the acoustic quality of sounds have been considered essential contributions for the location of the signal. For example, higher frequency sounds interact with the pinnae structures, resulting in changes in the distribution of acoustic energy over all of the frequencies for a complex sound. The pattern of these changes is a function of the angle and elevation of the sound source (Batteau, 1967, 1968; Belendiuk & Butler, 1975; Fisher & Freedman, 1968; Flannery & Butler, 1981; Hebrank & Wright, 1974; Musicant & Butler, 1984; Noble et al., 1997; Noble et al., 1998; Roffler & Butler, 1968; Saberi et al., 1991; Tonning, 1975). Musicant and Butler (1984) concluded that pinnae-based spectral cues comprised of frequencies greater than 4000 Hz, allow the listener to identify whether the sound source emanates from the front or rear quadrant of the horizontal plane. Because high-frequency sloping hearing loss continues to be the most common configuration of sensorineural impairment (Halling & Humes, 2000; Souza & Bishop, 2000; Turner & Cummings, 1999), it is important to ensure audibility for sounds of frequencies 4000 Hz and higher for these individuals. In providing amplification to do so, one is likely to occlude one or both conchae, reducing the important pinnae-based spectral cues in this 4000 Hz region. Therefore, returning information in this frequency region through restored audibility can be very important for localization. Subjects in Musicant and Butler's (1984) investigation were able to accurately locate a 4000 Hz low-pass noise when both conchae were occluded indicating that other spectral cues were available to the listener. A likely explanation is the spectral changes that result from the sound's diffraction around the torso (Gardner, 1973; Kuhn, 1979; Kuhn & Guernsey, 1983; Noble et al., 1998).

Sound is scattered by the body so that the sound pressure levels near it are different from the levels in the undisturbed sound field. Sound pressure level (SPL) transformations are the difference obtained by subtracting the SPL measured in the empty field from the SPL near the head or torso. In a summary of the impact of the head and torso on sound, Kuhn and Guernsey (1983) state that the human torso is reasonably hard acoustically below 2000 Hz. It becomes increasingly absorptive above this frequency (Burkhard & Sachs, 1975; Kuhn, 1979). With sound originating from in front of the listener, SPL transformations to the torso are generally positive, meaning more SPL around the body due to the torso for the low- to mid-frequencies reaching a maximum of approximately +3 dB SPL. The transformation becomes smaller as the frequency of the signal exceeds 5000 Hz and reaches a minimum of –4.5 dB SPL at 10 kHz (Young, 1974). When the sound originates from the same side of the listener that the microphone is on, a positive transformation ranging from about 4 dB SPL up to 2000 Hz to approximately 1 dB SPL at 8000 Hz, will be seen. This same pattern of positive SPL transformation is seen when the signal originates from the opposite side of the listener from where the microphone is but the entire signal is attenuated by about 5 to 8 dB SPL (Kuhn &Guernsey, 1983).

The human head is acoustically hard to at least 6 kHz or 7 kHz with transformations from a diffuse field ranging from –1 to +5 dB SPL. With the signal from the same side as the microphone, the directional gain ranges from +1 to +6 dB SPL (Burkhard & Sachs, 1975; Kuhn, 1979; Young, 1974).

A positive SPL transformation indicates that the actual sound pressure level of the signal is enhanced for the listener due to the presence of the object it reflects off of (in this case the head and/or torso of the body). When a sound is enhanced more on one side of the listener versus the other, the intensity differences should allow the person to better gage from which side the sound originated.

2.1.5.5. Contribution of Spectral Cues

The interaction of the various spectral cues on localization ability, particularly with respect to their role for individuals with hearing loss is not well understood. For example, subjects are unable to completely trade time for intensity (Hafter & Carrier, 1972; Hafter & Jeffress, 1968; Whitworth & Jeffress, 1961). This suggests that degradation of one cue may be compensated for by enhancement of others. Possibly, intact abilities to process the undisturbed cues allow normal localization despite degradation of other cues. A large body of literature exists that allows quantification of the influences of the listener, the environment, and alterations or differences in both on sound waves and the localization of them. Appendix C - Table 2 provides a synopsis of the goals, conclusions, and limitations of several of these studies.

2.1.5.6. Testing Localization Abilities

Two ways to test for localization include directional audiometry in an anechoic chamber with loudspeakers or phase audiometry in which headphones are used to deliver sound with simulated temporal delays. The fused auditory image using directional audiometry is perceived to be in the room, while the sensation of the image from phase audiometry is in the head of the listener. Lateralization of dichotic sounds towards the direction of the first arriving sound happens in listeners with normal hearing as soon as a difference in time of about 20-30µs or 2.3º phase shift is reached for free-field testing (Groen, 1969; Nilsson & Liden, 1976; Rosenhall, 1985). In a study by Nilsson and Liden (1976) mean delays for lateralization on the order of 47.9µs or 8.6º phase shift using a phase audiometry procedure and head phones were found. It has been argued (Nordlund, 1963) that the same degree of accuracy may not be attainable with phase audiometry because the sound is localized in the head of the listener.

Discrimination suppression is defined as the weakening of the discrimination of the lag sound's position in the presence of the lead sound (Freyman, McCall, & Clifton, 1998; Yang & Grantham, 1997a). Divenyi and Blauert (1987) and Blauert and Divenyi (1988) found that the most discrimination suppression occurred when there was complete spectral overlap of the lead and lag sounds. Suppression of the lag sound's position was small when the frequency of the lag exceeded the lead. Similarly, no suppression at all was noticeable when the frequency of the lag was below that of the lead. Consequently the authors proposed that discrimination suppression is frequency dependent and therefore the amount of suppression is directly related to the amount of spectral overlap of the lead and lag sounds. This has been referred to as the spectral overlap hypothesis (Yang & Grantham, 1997b).

In 1992, Divenyi found competing results to the original hypothesis. In this investigation he noted that there was more suppression of a 2000 Hz lag sound by a low frequency lead sound than by a lead sound of 2000 Hz. It was concluded that there must be some other factor that impedes lateralization of the lag sound when the lead sound is of a low frequency but not when it is of a high frequency. A second proposed hypothesis is known as the localization strength hypothesis. Here, the perceptual prominence of spatial information is quantified by measuring the interaural temporal difference (ITD) threshold of sounds in isolation; the lower the ITD threshold, the greater the localization strength of that stimulus. Localization strength is greater for low frequencies than for high frequencies. Stated differently, one needs less of a time gap between when a sound reaches one ear versus the other to tell where the sound originated from when the signals are of lower frequency versus when they are of higher frequency. For individuals with sensorineural hearing loss, this is compounded by the fact that their temporal resolution abilities are reduced due to the hearing loss.

Many studies done using headphones where the subjects' task was to indicate the apparent lateral position of the composite image inside the head are in agreement with the localization strength hypothesis (Scharf, 1974; Shinn-Cunningham, Zurek, Durlach, & Clifton, 1995; Yost, Wightman, & Green, 1971). In 1997, Yang and Grantham investigated which of the two hypotheses better predicted discrimination suppression in the free field. Results from part one of this experiment were consistent with the spectral overlap hypothesis. Localization strength in turn had no apparent effect on discrimination performance at this point. Because of the conflict in results with those of Divenyi (1992), they argue that localization strength is the primary factor when interaural time differences are the only cue, which is the case in phase audiometry. In the free field however, intensity and spectral cues also are available. In part two of this experiment, localization strength was manipulated while frequency was held constant. Results here are consistent with the localization strength hypothesis. This additional conflict in results gives rise to the argument that the procedure used to vary localization strength (varying rise times for the stimuli) may give rise to some other process besides just varying localization strength. One reasonable suggestion is that the spectral features associated with varying rise times are what underlie suppression discrimination. In summary, Yang and Grantham (1997) conclude that localization strength dominates in phase audiometry, while spectral overlap dominates for the free field, with localization strength operating as a secondary factor. In "real-world" situations (more similar to the free field), spectral overlap of signals (i.e., speech in a background of other speakers), poorer localization strength for higher frequency sounds, and reduced abilities in this frequency region due to hearing impairment, help to illustrate why individuals with hearing loss may have difficulty hearing speech-in-noise. Also, the presence of discrimination suppression interferes with localization abilities.

The lag sound does contribute to the fused auditory image in a dichotic signal. The contribution of the lag sound to the perceived location of the image is approximately 1/6 to 1/10 the size of the lead's contribution (Freyman et al., 1998). Blauert (1983) found that the lead/lag combination sound is different in qualities such as loudness, timbre, and spaciousness from a diotic sound. Freyman et al., (1998) examined the listener's ability to detect intensity changes in the lag sound. The data suggest that the precedence effect does not involve suppression of the lag sound's intensity contribution. The lag sound's contribution should allow the subjects to hear a larger, fuller, more spacious image as the level of the lag sound approaches that of the lead sound. Finally, the authors indicate that reflections can aid in speech communication by increasing the signal level reaching the ears.

The influence of the leading stimulus can be greatly weakened in the presence of noise in the free-field (Chiang & Freyman, 1998; Good & Gilkey, 1996; Leaky & Cherry, 1957; Thurlow & Parks, 1961) and under headphones (Babkoff & Sutton, 1966). Chiang and Freyman (1998) also found that the level of the lag necessary to produce a center image was less in noise than in quiet. This suggests that for time/intensity trading, less intensity for the lag sound is required to overcome the temporal advantage of the lead sound in noise. Additionally, Chiang and Freyman (1998) found that the noise increased the audibility of the echoed sound; evidenced by lower thresholds for the subject to report hearing a second sound as opposed to only one fused image.

2.1.5.7. General Findings

Localization and Age - Ability to localize decreases with increasing age (Cranford, Andres, Piatz, & Reissig, 1993; Cranford, Boose, & Moore, 1990; Gelfand, Ross, & Miller, 1988; Grose, Poth, & Peters, 1994; Grose, 1996; Pichora-Fuller & Schneider, 1991; Tonning, 1973; Tonning, 1975; Viehweg & Cambell, 1960). Cranford et al., (1990) found that elderly individuals performed worse than young subjects on tests of localization abilities when inter-speaker delays of .1 - .5 ms were present. No significant difference was found for inter-speaker delays of .7 ms or higher. Maximum inter-speaker delay used was 8 ms. This group of investigators performed an earlier investigation (Moore, Cranford, & Rahn, 1990) in which two subjects with Multiple Sclerosis (MS) were participants. The results from the elderly subjects in the present study compared well with the performance of the patients with MS. The authors suggest that demyelination, known to result in abnormalities in neural conduction and characteristic of patients with MS, also may contribute to the elderly subjects' poorer performance. Others (Cranford et al., 1993) have corroborated this theory of decline in temporal processing abilities in elderly individuals. Therefore, in experiments involving localization, it is important that groups be classified according to age, as this influence may confound the results obtained.

Localization and Hearing Loss - Various experiments have been performed to quantify any correlation between hearing loss and localization abilities. While in many studies the results are not extremely robust, the general statement can be made that localization is impaired to a degree in individuals with hearing loss regardless of type or configuration (Bosatra & Russolo, 1976; Groen, 1969; Hawkins & Wightman, 1980; Jongkees & van der Veer, 1957; Nilsson & Liden, 1976; Nordlund, 1964; Rosenhall, 1985; Roser, 1966; Shitara, Sata, & Kirikae, 1965; Tonning, 1973). For experiments involving localization abilities, it would lend greater control to the methods if subjects were selected as closely as possible for hearing loss type, configuration, severity, and symmetry.

Hawkins and Wightman (1980) discuss the possibility that it is the pattern of neural impulses at the point where binaural stimuli are compared that is disrupted by peripheral damage in individuals with hearing loss. This theory speaks to decreased frequency selectivity capabilities.

Correlational analyses of localization abilities and hearing threshold level in individuals with hearing loss have been conflicting. Some have found that localization abilities do not always relate to degree of hearing loss (Hawkins & Wightman, 1980; Tonning, 1975). Others note a significant decrease in performance with increasing hearing loss (Noble et al., 1994). Noble et al., (1998) found some correlation with hearing threshold level and performance in both the horizontal and vertical planes. In the frontal horizontal plane, the higher (worse) the threshold, the lower the localization accuracy at both 250 and 500 Hz signals at both 50 and 65 dB SPL presentation levels. In the lateral horizontal plane, similar results were noted but at only the 50 dB SPL presentation level. In the lateral vertical plane, at both intensities, there was a significant negative correlation with thresholds at 250-1000 Hz and a significant positive correlation at 2 – 12 kHz. Poorer hearing at high frequencies and better hearing at low frequencies were associated with better lateral vertical localization. Contrast measures also were obtained and show that the greater the contrast in low versus high frequency thresholds, the greater the localization accuracy. Duration of hearing loss does not correlate with localization abilities (Tonning, 1975; Viehweg & Campbell, 1960).

Localization and Speech Hearing in Noise - A positive relationship has been suggested between speech hearing in competing noise and localization abilities in the free field (Noble et al., 1997). Hirsch (1950) found an advantage for speech hearing in noise due to the spatial separateness of signals. Others also noted this phenomenon (Bronkhorst & Plomp, 1989;

Carhart, 1965; Dirks & Wilson, 1969; Freyman, et al., 1998; MacKeith & Coles, 1971). Freyman et al., (1998) state that intensity properties of echoes signify aspects of the space one is in. Additionally they cite Blauert (1983) who showed that reflected sounds enhance the overall quality of complex sounds. Saberi et al., (1991) suggest improvement may occur from increases in signal-to-noise ratio in specific frequency bands due to directionally different pinna filter effects. Other investigators suggest that a binaural advantage resulting mainly from interaural time and intensity differences caused by the diffraction of the signal by the head may be responsible for the improvement in the overall quality of complex sounds (Bronkhorst & Plomp, 1989; Carhart, 1965; Dirks & Wilson, 1969; MacKeith & Coles, 1971). Plomp and Mimpen (1981) found that, binaural gain increases to about 10 dB SPL when the noise is presented to the side of the listener. Bronkhorst and Plomp (1989) investigated the separate contributions of interaural time and intensity differences to binaural gain in people with normal and impaired hearing. They found, for normally hearing listeners, interaural level differences have a greater effect than interaural time differences and the effects of the two are not additive. Additionally, subjects with hearing impairment benefited as much from temporal differences as those with normal hearing but not as much from intensity differences. They attribute reduced ability to take advantage of level differences to a combination of the frequency dependence of the head shadow effect (which is greater for high frequencies) and the presence of high frequency hearing loss.

Colburn and Hausler (1981) suggested that binaural processing for speech might be further limited if the signal for one ear is distorted and this is compared to an intact signal from the other ear. They believe this may be the cause for the observation of symmetrical loss of hearing sensitivity accompanied by asymmetrical speech recognition scores (with no retro-cochlear pathology). McCullough and Abbas (1992) sought to investigate the relationship between asymmetrical speech recognition scores and binaural advantage of nonsense syllables. They found diverse representations of binaural advantage and concluded that it cannot be predicted on the basis of asymmetrical speech recognition scores. Because of the uncertainty of the role of spatial separateness in free-field speech hearing, Noble et al., (1997) investigated the possibility that listeners may be exploiting different alterations in the signal versus the noise rather than finding speech easier to understand because it is heard as coming from a different place. Their results revealed that subjects with mild sensorineural hearing loss and those with conductive/mixed hearing loss required only one decibel more signal-to-noise benefit than those with normal hearing to perform similarly on tests using non-separated speech in noise. Those subjects with more severe sensorineural hearing losses required an average of 3.5 dB better signal-to-noise ratio to perform as well. Also, all hearing loss groups showed little or no separation benefit. They conclude that spatial hearing does play a limited role in speech hearing in noise.

Localization has a significant role in the sensing of one's environment. As this is a primary purpose of being able to hear, the effects of spectral and spatial cues as well as hearing impairment and the attributes of the listener on localization abilities are important to consider. These considerations are not only important as they pertain to gaining an understanding of hearing impairment in general, but also for understanding how the listening environment created through various types of amplification technology effects the localization abilities of individuals with hearing impairment.

Hearing aids are used to amplify sounds that are inaudible to the individual with hearing impairment. As stated several times herein, sensory hearing loss is not only a matter of sensitivity. Therefore, technology is continuously being updated to include potential solutions to various selectivity issues of hearing impairment. The following section will review the literature that speaks to the impact of hearing aids on localization and speech hearing-in-noise.

2.2. Hearing Aids

2.2.1. Hearing Aids and Localization

Hearing aids can add to the disturbance of sound localization function (Byrne et al., 1992; Noble & Byrne, 1990; Noble et al., 1998). Noble et al., (1998) argue that one reason for this is that parts of the hearing aid physically occupy the concha which has a critical role in localization. Another reason is that pinnae transformations in localization take place at 4 kHz and hearing aids do not amplify well at or beyond this frequency. To this end, Byrne and colleagues investigated open earmolds and localization function in both individuals with low-frequency hearing loss (Byrne, Sinclair, & Noble, 1998) and those with high frequency hearing loss (Noble et al., 1998). In both investigations the findings revealed that aided localization was restored to unaided levels with open earmolds and limited further benefit was seen with sleeve-type open earmolds.

Noble et al., (1995) examined self-assessed everyday disability resulting from or associated with impaired localization capacity and concomitant handicaps. They compared results for individuals with no hearing loss and for individuals with hearing impairment with conventional omni-directional amplification and without. Evidence from other comparative studies suggests that there is reason to expect that impairment of localization abilities should affect the experience of hearing in the everyday environment (Eriksson-Mangold et al., 1992;

Lutman, Brown, & Coles, 1987; Noble & Atherley, 1970). Disabled localization has emerged as a significant factor in studies of everyday hearing disability including in the formation of the Hearing Measurement Scale (HMS) (Noble & Atherley, 1970), in profiles of self-assessed hearing disability (Lutman et al., 1987), and on a 25-item form of the Hearing Measurement Scale (Eriksson-Mangold et al., 1992). A questionnaire was developed by Noble et al., (1995) consisting of questions divided into three sections. Section one explored self-perceived disabilities (as defined by the World Health Organization [WHO], 1980) associated with decreased localization abilities; section two allowed quantification of self-perceived handicap (as defined by the WHO, 1980) directly attributable to localization disability. Finally, section three questions were designed to explore self-perceived speech hearing disabilities. Correlational analyses were computed between all three sections and with the hearing threshold levels of the subjects. Increased hearing loss was associated with greater localization disability. The correlation between localization disability and handicap due to localization disability was high. This indicates that those who perceive themselves to be disabled in terms of localization also experience handicaps that impact their quality of life because of this specific disability. The correlation between localization disability and speech hearing disability also was high; implying that when localization disability was high, more problems with speech hearing were noted. Speech hearing disability and handicaps due to localization disability did not correlate well. The self-assessed ability of people with bilateral hearing loss to localize without hearing aids is less than that of people with no hearing loss. This disability is significantly associated with handicaps such as feelings of confusion or loss of concentration. Localization ability and speech hearing ability are rated as significantly improved with either one or two hearing aids.

In theory, hearing aids fitted binaurally should offer an advantage regarding localization in the horizontal plane by preserving the interaural spectral differences of the sounds. Results from studies have consistently shown this to be the case (Byrne & Dermody, 1975; Dermody & Byrne, 1975; DiCarlo & Brown, 1960; Heyes & Ferris, 1975; Markides, 1977; Sebkova & Bamford, 1981). Byrne et al., (1992) show that this effect is further related to hearing threshold level. Their results show a significant bilateral advantage for individuals with four-frequency hearing threshold averages over 50 dB HL with both BTE and ITE type hearing aids, from both frontal and side angles of incidence. Also, the suggestion could be made for a potential contribution of binaural cues to vertical plane localization as evidenced by equal performance in this plane as was achieved in the horizontal plane (Byrne et al., 1992).

Investigations of the impact of amplification on localization reveal a positive relationship. Further research will help to determine if this relationship also exists with more advanced technology that is designed to combat problems with understanding speech-in-noise.

2.2.2. Hearing Aids and Speech Perception in Noise

Often times, it is of paramount importance to people with hearing impairment to be able to communicate easily. This requires being able to understand speech in a variety of listening environments. As mentioned earlier, a principle complaint of people with hearing impairment is the inability to understand speech in noise (Kochkin, 1993). Using a hearing aid typically allows both the speech and the noise to be amplified and does not contribute to enhancing the signal-to-noise ratio required by hearing-impaired listeners. Therefore, efforts have been made to develop circuitry that helps reduce the effects of background noise. Among the various types of signal processing that aim at this are short-term Weiner filtering, transformed spectrum subtraction, split-band spectrum subtraction, noise reduction using sinusoidal modeling, adaptive noise canceling, and directional microphones. These types of processing of the signal will be reviewed with more detail for the more popular techniques.

2.2.2.1. Short-term Wiener filtering

Short-term Wiener filtering uses a frequency filter to separate the speech from noise from a single microphone input. Wiener (1949) established that for the case of statistically stationary sounds, signal-to-noise ratio could be maximized using a filter of this type. Speech is not stationary but, Levitt et al., (1993) proposed that it is possible to think of it as such if it is considered over short intervals of time. Their investigation showed that 50% of the subjects demonstrated a significant improvement in consonant recognition with an equivalent improvement in SNR of approximately 5 dB with short-term Wiener filtering. They hypothesize that the reason only half of the subjects demonstrate this is because some individuals with hearing impairment have larger critical bands and the increase in signal-to-noise ratio resulting from the use of a short-term Wiener filter within a critical band is greater for larger critical bands. These results suggest that an optimum filter (not the Wiener filter) will depend on both the acoustic characteristics of the signal and the noise and also on the audiologic characteristics of the listener.

2.2.2.2. Transformed Spectrum Subtraction

A version of this type of technology, known as INTEL, is currently used with listeners with normal hearing who need to listen in noise (Weiss & Aschkensay, 1978). With this processor, the spectrum of the signal is obtained with Fast Fourier Transform (FFT). The phase spectrum is stored while the amplitude spectrum is subjected to non-linear transformation. This transformed signal is then converted back to the time-domain, using inverse FFT. A decision is made based on the structure and intensity of the amplitude spectrum about whether the signal is speech plus noise or just noise. If it is only comprised of noise, then it is used to compute a running average of the spectrum of the noise. If it is comprised of speech plus noise, the most recent averaged spectrum of noise is subtracted from this signal. The signal is then converted back to its amplitude spectrum, the phase spectrum is restored to it, and a final inverse FFT is used to obtain a time waveform that is delivered to the listener. In 1986, Levitt et al., found that while similar performance on the Nonsense Syllable Test (NST) was found both before and after INTEL processing, SNR was significantly improved with processing. Unfortunately it was found that noise-like portions of the speech signal (e.g., fricatives and plosive bursts) had been removed from the final signal by the processing. This removal occurred mostly in the high-frequency region. Therefore Levitt et al., (1993) modified the technique into what is known as the split-band system.

2.2.2.3. Split-band Spectrum Subtraction

With this processing, transformed spectrum subtraction is applied only to signals with energy below 2800 Hz. Signals with energy above this frequency are passed without processing. The two bands are added before conversion back to an analog signal. Results from a comparison of the single-band system and split-band systems with a no-processing system showed that, despite poorer NST performance with the single-band, and only similar NST scores using the split-band, subjects consistently preferred the processed sound over no-processing.

Problems with using this type of circuitry with hearing-impaired listeners will involve deleteriously altering the high frequency information with Transformed Spectrum Subtraction. If one used Split-band Spectrum Subtraction, the noise from the high-frequency section would not be reduced at all and this is typically the frequency region of concern for individuals with hearing loss.

2.2.2.4. Noise Reduction Using Sinusoidal Modeling

This approach to improving speech intelligibility in noise is based on sinusoidal modeling of the speech signal (McAulay & Quatieri, 1986). Here the speech is divided into overlapping segments. FFT is computed for each segment and the number of spectral peaks is identified. The waveform is re-synthesized using modeled sinusoids having the same frequency, amplitude, and phase as the spectral peaks. This allows direct access to all of the important speech signal parameters. However, Levitt et al., (1993) found that, in quiet, unprocessed signals were the most intelligible. For speech in noise, when 16 sinusoids were used for modeling, the signal was equally intelligible to when no processing was used. There was systematic reduction in intelligibility with decreases in the number of sinusoids used (i.e., eight sinusoids and four sinusoids).

2.2.2.5. Adaptive Noise Canceling

Hearing aids with self-adaptive noise filters use two channels to help reduce the noise. With this processor, an incoming sound is sampled, the noise spectra present in this reference channel are identified, and inverse of these spectra are approximated and used to cancel any noise in a second (primary) channel. The processor uses predetermined thresholds to identify the fast temporal variation of speech versus the slow variations of noise and multi-talker babble. Limitations with this type of circuitry in hearing aids do exist. First, the presence of noise in the primary channel may not be correlated with the noise received and filtered in the reference channel. This will happen when the noise is generated internally from the hearing aid or from more than one source (Weiss, 1987; Levitt et al., 1993). Similarly, the presence of speech components in the reference channel will interfere with the filtering process (Weiss, 1987). Also, it takes time for the filter to converge on the environmental setting and minimize the noise. If there is head movement, the filter may not have time to converge on the present setting before it needs to do so for the next. Increased noise will persist until the filter adapts to the new conditions (Weiss, 1987; Levitt et al., 1993). Finally, the finite length of the filter limits the noise attenuation that can be achieved in reverberant rooms (Weiss, 1987). Stein and Dempesy-Hart (1984) examined the effects of this type of processing on speech intelligibility under five noise conditions. Their results reveal the most marked improvement in low-frequency band-pass noise and cafeteria noise. Additionally they note that individuals with normal hearing or only mild-to-moderate sensorineural hearing losses demonstrate greater gains than those individuals with sloping high-frequency losses.

Another way to achieve this type of signal processing is with two microphones. One serves as the primary microphone and the other as the reference microphone. The reference microphone is placed near the noise source and the primary picks up both speech and noise. The reference input is passed through a filter and the output is subtracted from the primary input. The noise is "cancelled". This type of processing only can be used with hearing aids if the microphones differ in their directional characteristics (Weiss, 1987). Theoretically a directional microphone faces the noise source and an omni-directional microphone faces the primary input.

Schwander and Levitt (1987) and Levitt et al., (1993) found that this type of signal processing allows the most significant improvements in only moderately reverberant rooms. This finding was true regardless of head movement. Hearing aids with directional capabilities will be discussed in detail in a following section entitled "Directionality to Improve Signal-to-Noise Ratio".

Another proposed way to use adaptive noise cancellation and minimize speech in the reference input is to permit the filter to only adapt to noise inputs when the speech is absent. This combined with a directional microphone will minimize the spectral distortion of the speech (Weiss, 1987). Weiss (1987) examined the use of this type of combination adaptive noise canceling and found that for an anechoic room, the processor was able to provide significant attenuation of sounds generated by at least one of three noise sources. The processor was inferior when tested in a reverberant environment.

Each of the signal processing techniques described above attempts to reduce noise by detecting the differences between speech and noise and canceling noise or enhancing speech accordingly. Among the problems present in this type of approach are, 1) an inability to detect the differences correctly, 2) partial removal of the speech signal or partial enhancement of the noise, and 3) constraints of the technology like convergence time and inferiority in reverberation. Directional microphone technology uses a different approach to enhancing the speech signal and is described in the following section.

2.2.3. Directionality to Improve Signal-to-Noise Ratio

The directional microphone is designed in such a way that it is more sensitive to sounds coming from one direction (typically, in front of the listener) than from the other directions and in this way improves SNR. Hearing aids with directional microphones were first introduced in the 1970s. Investigations done in this decade show significant improvement in speech discrimination scores for listeners with hearing impairment using conventional directional aids with a single-microphone at moderate SNRs (e.g. –6, 0, 5,10, etc. dB) (Mueller & Johnson, 1979; Nielsen, 1973; Sung et al., 1975). In the early 1980s, publications showing a preference by the listener for hearing aids with conventional single-microphone directionality were available (Hillman, 1981; Mueller, 1981; Mueller et al., 1993). Unfortunately directional amplification devices did not attain the clinical acceptance that might be expected from these promising investigations (Bilsen, Soede, & Berkhoudt, 1993). This was likely due to an explosion, at this time, of custom products in the mid-1980s. These popular solutions could not support the directional technology at that point in time. Development of highly directional systems has since taken place. Appendix D - Table 3 highlights the specifics of investigations into the benefit available from directional amplification systems.

2.2.3.1. Ways to Measure Microphone Performance

Various ways to quantify the directionality of microphones include polar sensitivity plots, the front-to-back ratio (FBR) metric, the front-to-angle ratio (FAR) metric, the Directivity Index (DI), and the Articulation Index weighted Directivity Index (AI-DI).

Polar Sensitivity Plots - A polar sensitivity plot is a graphical representation of the output of the microphone as the signal source arrives from different azimuths (Valente, 1999). The polar sensitivity can be measured with the hearing aid suspended in the free field or on the “head” of KEMAR. The measurement will be very different depending on which procedure is used and the impact of the head and torso will contribute significantly to it.

Microphone designs are divided into four categories. They are the cardiod pattern, the hypercardiod pattern, the supercardiod pattern, and the bidirectional pattern.

The polar plot of a cardiod microphone will reveal attenuation (null) at 180° (directly behind the listener). This means that maximum sensitivity will be allowed when the signal is directly in front of the user (0°). Progressive attenuation will be employed as the signal rotates away from 0° and will reach its maximum for signals presented from the rear of the listener.

A hypercardiod pattern obtained in the free field will show significant attenuation when signals come from between 130° and 230°. Nulls are represented at 110° and 250°. What is referred to as a lobe is evidenced at 180°. A lobe illustrates some amplification when signals arrive from behind as compared to the cardiod pattern. The amplification in the lobe is not as great as that for signals from azimuths in front of the listener. When the polar plot of a hypercardiod microphone is obtained with the system placed on the "head" of KEMAR the null moves to 270° for 500 Hz signals and disappears with 4000 Hz signals (Valente, 1999). This illustrates the importance of obtaining polar plots with a head and torso present in the sound field.

In general, attenuation for cardiod and hypercardiod microphones is greater at 500 Hz than at 4000 Hz. This is especially true for the in-the-ear style of hearing aids (Valente, 1999).

The supercardiod pattern is very similar to the hypercardiod pattern except that the lobe is shallower. This provides greater improvement in noise from directly behind the listener than the cardiod or hypercardiod (Valente, 1999).

The bidirectional pattern has nulls for signals coming from 90° and 270°. Two equal lobes are present.

Front-to-Back Ratio - The front-to-back ratio (FBR) is the difference between the frequency response of the microphone when the signal is presented from the front and the frequency response of the microphone when the signal is presented from the rear. This type of measurement would not be accurate if obtained for microphones with hypercardiod, supercardiod, or bidirectional patterns (Valente, 1999). Mueller and Johnson (1979) point out that significant improvement provided by conventional directional microphones is dependent on the degree to which the microphone attenuates signals from behind as evidenced by different results in SNRs obtained from microphones with different FBRs.

Front-to-Angle Ratio - Similar to the FBR, the FAR could be defined as the difference between the frequency response of the microphone when the signal is presented from the front and the frequency response of the microphone when the signal is presented from other predefined angles of incidence. These measures may be more descriptive than the FBR of the directionality of the instrument if one considers that, in reverberant environments, the directional advantages of directional microphones can essentially disappear due to the background interference (Madison & Hawkins, 1983; Studebaker, Cox, & Formby, 1980).

Directivity Index - The Directivity Index (DI) represents the ratio in decibels of the microphone's output for signals from the front to sound originating from all directions. This metric correlates with predicted improvement in SNR (Bilsen et al., 1993; Valente, 1999).

Articulation Index Weighted Directivity Index - The Articulation Index (AI) (ANSI S3.5, 1969) provides a measure of the percentage of speech energy that is audible to the listener based on threshold and signal level. The AI provides different weights to the contribution of each frequency. In the AI-DI, the DI at each frequency is multiplied by the AI weight at that frequency. A root mean square sum of the resulting products gives one number. This metric will roughly correspond to the improvement in SNR that can be measured for speech tests conducted in real-world situations (Soede, 1990). Killion (1997a) suggests that where there is a better direct-to-reverberation ratio, the improvement in SNR may be greater than that predicted by the AI-DI.

It is important that measures of directionality be obtained and/or verified with each instrument for each individual. Polar Sensitivity Plots are a reflection of the pattern of the directional enhancement of the environment surrounding the listener that should be provided by the instrument. This information is often obtained and provided by manufacturers. Because this type of measurement is variable based on the physical attributes of the hearing aid user, and because it is necessary to perform these measurements in an anechoic chamber, the polar sensitivity plot is difficult to obtain in the standard clinical setting.

Also clinically complex to obtain are DI and AI-DI measurements. However, these measures do provide a great deal of information regarding the directionality of the instrument while considering the physical presence of the listener. Additionally, they allow prediction of the expected increase in signal-to-noise ratio and subsequent improvement in speech recognition. While the FBR is more easily obtained in a standard clinical setting, this measurement does not allow quantification of the directionality provided by the microphone for sounds originating from angles of incidence other than from directly behind the listener. FARs appear to provide the greatest detail about the directionality of the instrument with the most easily implemented procedure in a standard clinical setting.

2.2.3.2. Microphone Types

As stated earlier, much improvement of the directivity of microphones has taken place. The various types of microphones have been divided into several groups.

Omni-directional Microphones - Omni-directional microphones have one sound inlet and signals are equally processed regardless of the azimuth from which they originate.

Single Directional Microphones - These microphones have two sound inlets (in one microphone) leading to separate cavities divided by a diaphragm. This diaphragm senses differences in the air pressure between the cavities. Sounds originating from the rear will activate both ports eventually, but will reach the rear port first. To prevent the rear inlet signal (noise) from activating the diaphragm before the front inlet signal, an acoustical time delay is applied to the rear inlet signal. This assures that all contributions (rear inlet and front inlet) from signals incident to the rear reach the diaphragm at the same time. Those parts of the signal that are equal in SPL on either side of the diaphragm will not displace the diaphragm. Signals incident to the front of the listener will arrive at the front port first, will not be subject to acoustical time delay, and will arrive at the diaphragm providing greater intensity on one side and will displace the diaphragm. These displacements will represent the primary output of the microphone.

Dual-microphone systems - These systems consist of two, perfectly matched, omni-directional microphones. Performance is improved by subtracting the output of the rear microphone (the noise) from that of the front microphone and adding a time delay to the output of the rear microphone.

Three-microphone systems – This system consists of three, perfectly matched, omni-directional microphones. It works similarly to the way the dual-microphone system works but because of the additional input of the third microphone, an improvement of 2 dB in the AI-DI calculation can be expected.

D-Mic - This technology was recently introduced (1997) by Etymotic Research for use in in-the-ear hearing aids. It is a dual-microphone system but with one omni-directional microphone with one inlet port and one hypercardiod directional microphone with two inlet ports that functions as described in the conventional directional microphone section.

Multi-Microphone arrays - These types of arrays are currently used in experimental hearing aids. They also are known as beamformers and consist of 2 to 17 omni-directional or directional microphones. Research shows no further benefit to directivity beyond five microphones (Bilsen et al., 1993; Soede, Berkhout, & Bilsen, 1993).

Adaptive directional microphones - Available only in dual- or three- microphone systems, the polar pattern characteristics of this type of system are continually adjusted according to the properties of the environment and depend on the summed outputs of the separate microphone signals. Sounds from certain directions (i.e., not in front of the listener) carry less weight in the algorithm and as such the "noise" is suppressed. The null(s) of the polar pattern are constantly adjusted to the angle of the highest level of interference (Soede et al., 1993; Bentler, Palmer, & Dittberner, 2004).

2.2.3.3. Findings from Investigations of Benefit from Directional Amplification

The earliest directional microphone systems were shown to have an advantage over omni-directional microphones (Sung et al., 1975). These results were greatest for anechoic conditions

(Studebaker et al., 1980). The advantage decreases as reverberation time increases and as speech and noise originate from diffuse sound fields (Bentler et al., 2004; Hawkins & Yacullo, 1984; Madison & Hawkins, 1983; Novick, Bentler, Dittberner, & Flamme, 2001; Pumford et al., 2000; Ricketts & Dhar, 1999; Ricketts, 2000a). A sound field (with the exception of the free-field) consists of two parts: direct and reverberant. As distance from the source of sound increases, direct sound energy decreases until reverberant or reflected sound energy predominates. The critical distance is defined as the point in a room beyond which the level of the reflected sound exceeds that of the direct sound. It follows that the presence of these disadvantageous listening conditions would reduce the effectiveness of directional microphone amplification. Recall that the problem facing the listener with hearing impairment is compounded by reduced frequency selectivity, temporal resolution, and localization abilities. If the distance between the listener and the speaker is great, and the signal-to-noise ratio less than optimal, problems with spectral overlap and inaudibility of the signal will render even directional technology not very useful.

Hawkins and Yacullo (1984) hypothesized that the FBR will be optimal when reflected energy is at a minimum. They predicted that the directional microphone advantage can be enhanced in a room with a long reverberation time if the speaker-to-listener distance does not exceed the critical distance. They found substantial individual differences in susceptibility to reverberation. Leeuw and Dreschler (1991) hypothesized that the critical distance might be useful in predicting the advantage of the directional microphone for speech intelligibility but found that this simple model does not predict the advantage for all room positions.

Recent technological advancements to improve the directional abilities of directional microphones have resulted in the multi-microphone array, wearable dual-microphone systems, and adaptive directional microphones. The wearable dual-microphone systems have been developed to allow the user to toggle between directional and omni-directional amplification. With adaptive directional microphones the polar pattern changes depending on the location of the noise source. Results from investigations into the benefit provided by these systems in terms of improved SNR and subsequent improvement in speech recognition in noise are promising (Amlani, 2001; Bentler, Egge, Tubbs, Dittberner, & Flamme, in press; Bilsen et al., 1993; Greenberg & Zurek, 1992; Helle, 1986; Kompis & Dillier, 1994; Peterson, Durlach, Rabinowitz, & Zurek, 1987; Ricketts & Henry, 2002; Schwander & Levitt, 1987; Stadler & Rabinowitz, 1993; Weiss, 1987).

The dual-microphone system is currently much more popular in terms of its utility as a wearable system and several commercially available hearing aids that incorporate a combination of both omni- and dual-microphone directional modes are available. Valente et al., (1995) report an average improvement in critical SNR of 7.4 to 8.5 dB using a dual-microphone system in comparison to using omni-directional microphones. These figures are nearly double those found by Madison and Hawkins (1983) and Hawkins and Yacullo (1994) who used single two-port conventional directional microphones in comparison to omni-directional systems. While Valente et al., (1995) caution that some of the variability in the results of the different studies can be explained by differences in the speech material used, they claim that use of contextually rich material more closely reflects the real-world potential of benefit from a system in noise. Additionally, they noted an improvement in DI for the dual-microphone system (4.0 at 500 Hz and 2.5 at 4000 Hz) as compared to a single-microphone conventional directional system (2-3 at 500 Hz and 0 at 4000 Hz).

In a similar experiment using even more realistic and less ideal listening situations, Wouters et al., (1999) also found a significant improvement in terms of critical SNR with a switchable hearing aid in the directional mode versus the omni-directional mode. Because they found no significant differences between subject performance in the omni-directional mode and the subjects' own omni-directional hearing aids it can be concluded that the benefit comes directly from the directivity properties of the dual-microphones.

An investigation by Preves et al., (1999) provides further evidence that the critical SNR improvement found with a dual-microphone directional system is present whether the directional mode frequency response is equalized with the omni-directional mode response or not. Although benefit is realized in both conditions, greater benefit was seen in the equalized condition.
Including adaptive directional technology in the comparison, Ricketts and Henry (2002) found improved speech recognition performance with adaptive and non-adaptive directional processing over that measured with omni-directional processing across four listening conditions designed to simulate those found in the real world (diffuse noise, noise from two speakers in back of the listener, noise from two speakers to the sides of the listener, and a changing noise source position). A prominent advantage for adaptive over non-adaptive directional processing was found when the noise originated from the sides of the listener in both the fixed and changing-position noise conditions.

Bentler et al., (2004) included adaptive directional processing in a three-microphone system in a comparison of performance on speech-in-noise tasks and found that when the noise source was moving around the listener, only this system allowed a group of individuals with mild-to-moderate hearing impairment to perform similarly to a group with normal hearing. The other systems used in the comparison included omni-directional processing, dual-microphone fixed directional processing, dual-microphone adaptive directional processing, and three-microphone fixed directional processing.

Because of limitations with the processing and/or logistics of wearing some of the noise-reduction circuits described in the previous section, one might argue that directional microphone systems, specifically those that allow the wearer to choose the directional setting of the aid, currently are the most promising technology for combating the speech-in-noise problem. What influence these types of hearing aids will have on other aspects of hearing (i.e., localization abilities) has yet to be determined. While improving the speech-in-noise issue is certainly a worthy goal, the potential deleterious effects listening directionally may have on other properties of hearing may be significant to the quality of life of those with the disability.

2.3. THE PSYCHOLOGY OF DISABILITY AND REHABILITATION

Choosing a course of rehabilitation should involve not only examining the nuances of the disability itself, and the best remediation for the disability based on those nuances, but also the psychological impact both of having the disability and of the subsequent course of treatment. The psychology of disability includes the experiences of the individuals with the disabilities and, the influence of the behavior of nondisabled individuals and professionals. Meyerson (1988) illustrates this point,

> "There are differences between the disabled and other minorities…Blacks and Hispanics in the United States are clearly minority groups. From birth on, practically all experience the cohesion, the identity, the shared treatment and fate of the group to which they belong. Even if they are adopted…they are usually aware of their heritage and psychologically are members of their racial or ethnic group. The population of people with disabilities is markedly different. Their parents, siblings, extended family, and associates usually are nondisabled people. A child with a disability may not know for years that other people with similar

> physiques exist in this world. For adults who are newly disabled by accident or disease, a sense of community with others in similar situations is unlikely to exist" (p. 180-181).

To illustrate the specific experiences of individuals with hearing and speech impairments, Collings and Markova (1999) note that,

> "because of the limited communication resources of impaired speakers, misunderstandings can be frequent and maintenance of the conversation problematic… talking about something new presents difficulties for understanding. Both participants may confine the conversation to what is already 'known', and what, therefore, can be safely (unproblematically) talked about. This has implications for the substance and quality of impaired speakers' everyday interactions; and for their own, and others', perception of their competence as interactants" (p. 339-340).

This helps to elaborate the significance that the behavior of others, when interacting with a person with a disability, can have on the psychological health of that person.

The word rehabilitation implies a restoration to a former condition. Defined in specific context, its meaning implies that it will restore a person to a former condition which tended toward normalcy (Alpiner, 1979). Unfortunately, what many rehabilitation professionals forget (or never consider) is the social identity and individuality of the person they are treating. Understanding disability through a social paradigm offers opportunities to reframe the way professionals define problems related to disability (Gill, Kewman, & Brannon, 2003). Most commonly, from both the psychological and academic points of view, a physical handicap has been analyzed and compensated for as just that, a physical handicap. Blindness has been defined as simply loss of sight, deafness the absence of hearing. But it is important to remember that many of our organs (i.e., the eye and the ear) are not just physical organs but also social ones. As there is a movement away from the marginalization of individuals with disabilities, many call for a shift from viewing disability as a medical problem located completely in the individual to viewing disability as a limitation produced by the complex interaction between individual difference and the social environment (DePoy, 2002; Dowrick & Keys, 2001; Gill et al., 2003; Hahn, 1996). Therefore the problem of handicap must be posed as a social problem because the social aspect of their function may be paramount and central to the impaired individual (Vygotsky, 1987).

The effect on the social aspects of the life of the individual with impairment can be gleaned through an examination of what seem to be the most prominent, negative, psychological consequences of disability and handicap. There are fifty-four million people in the U.S. who have been marginalized in society because of their disabilities (Dowrick & Keys, 2001; US Bureau of Census, 1999). People with disabilities are much more likely to live at or below the poverty level than people without disabilities. Regardless of age, disability is far more prevalent among those with less than an eighth-grade education than among those with a college degree. At all education levels, disability is associated with low rates of work force participation and with lower earnings for those who are employed (Asch, 1984). Only 26% of adults with severe disabilities (18-64 years of age) work full or part time (Dowrick & Keys, 2001; US Bureau of Census, 1999). Many clinicians agree that depression and withdrawal with resultant isolation are the most prevalent psychological responses to severe hearing loss and reports of nervousness, anxiety, heightened fearfulness, and irritability are common in accounts of persons with hearing loss.

Alpiner (1979) argues that,

> "…the audiologist has to be aware of all affecting factors in the rehabilitation process. We do not create the factors found in hearing-impaired persons, we inherit them. Although the mission is to remediate, we do not remediate alone because there may be little our efforts can accomplish regarding physiologic problems, environmental constraints, and economic limitations" (p. 178).

This is not to say that people with disabilities do not need help. However, when the professional and the individual with the disability are able to work together to enhance the cycle of expectation about disability and treatment, the handicaps that overlay the disability will dissolve and the barriers will give way to opportunities.

The primary goal of this research is to uncover potential handicaps that are often left unexplored as rehabilitation professionals (researchers and clinicians alike) attempt to remediate hearing loss with hearing aids. As technology advances, ameliorating the most prominent complaint of the individual with hearing loss (inability to understand speech-in-noise) continues to be the primary objective of the hearing aid fitting. It also is important to determine if new technologies create or intensify other effects that could significantly compound the negative, psychological and/or social impact of the disability.

The following sections detail the methods and procedures used to reach the goal of determining the impact of listening directionally on activities of daily living and feelings of safety and isolation among older individuals with impaired hearing. Also, the success of listener discretion of the directional properties of the environment at eliminating any self-perceived disabilities or handicaps were evaluated.

3. PRE-EXPERIMENT

3.1. INTRODUCTION

The outcome measures for the main experiment were responses to an untitled questionnaire (Noble et al., 1995) designed to examine self-perceived everyday disability resulting from or associated with impaired localization capacity and concomitant handicaps. This questionnaire consists of items divided into sections. Section I explores self-perceived disabilities (as defined by the World Health Organization [WHO], 1980) associated with decreased localization abilities. Section II allows quantification of self-perceived handicap (as defined by the WHO, 1980) directly attributable to localization disability. By observing the responses of individuals with hearing impairment both with conventional omni-directional amplification and in the unaided condition, a high positive correlation between localization disability and handicap due to localization was found (Noble et al., 1995). This indicates that those who perceive themselves to be disabled in terms of localization also experience handicaps that impact their quality of life because of this specific disability. This questionnaire appears to be an appropriate tool to investigate self-perceived disabilities and handicaps, associated with impaired localization, among individuals with hearing impairment. This outcome measure was the focus of the pre-experiment where the purpose was to establish the construct validity, internal consistency reliability, and test/retest reliability of Sections I and II of the questionnaire. Another self perception tool, developed by Gatehouse and Noble, (2004) known as the Speech, Spatial and Qualities of Hearing Scale (SSQ) is designed to measure a range of hearing disabilities across several domains (hearing speech, spatial hearing, and quality of hearing). The spatial hearing section is quite similar to the questionnaire evaluated in the pre-experiment. A separate section, comprised of 12 questions has been designed to determine level of handicap has been used in comparison with the SSQ, however these questions are not specific to handicap that is associated specifically with localization disability. Two similar sets of questions (Ricketts, Henry, & Gnewikow, 2003), designed to be new subscales of the Profile for Hearing Aid Benefit (PHAB) (Cox, Gilmore, & Alexander, 1991), were developed to specifically address the situations in which directional hearing aids may provide different degrees of benefit than omni-directional hearing aids. However, these questions do not uncover potential localization disabilities or handicaps; therefore the present questionnaire is more appropriate for doing so and was chosen for the main experiment outcome measure.

A measure is not useful in research or for documenting a clinical intervention unless reliability and validity are established. In a paper from 2001, Flamme discusses the importance of knowing and understanding the psychometrics of the outcome measures one plans to use in clinic or in research. The goals of Flamme's study were to examine the relationship among three hearing traits (direction and distance hearing, soft sounds hearing, and understanding in noise hearing) while also estimating the amounts of trait-related, method-related, and other influences on tests designed to return estimates of these traits. In so doing, Flamme shows that the internal consistency reliability of Section I of the questionnaire developed by Noble and colleagues (1995) is .93 as determined by applying Cronbach's alpha. There are no published psychometric data for Section II of the questionnaire.

Internal consistency reliability is estimated by computing the correlations among items on a scale; the stronger the interrelationships, the more likely that the test is consistent. Item covariance is a measure of the distribution of any two items on a given scale. Cronbach's alpha examines the covariance of all possible pairs (e.g., item one and item two, item one and item three, item two and item three, etc.) on a given scale.

Test/retest reliability refers to the temporal stability of a scale. This means that the test is just as likely to produce valid and consistent results at one administration as it is to do so at a subsequent administration. This type of reliability is important if one means to use a measure on multiple occasions to, for example, show the efficacy of treatment.

The validity of this scale has not been addressed. Assessing validity often is a difficult task. Construct validity is used to draw an inference from test scores to a psychological construct. The intended independent variable is the construct (in this case localization abilities); while the proxy independent variable is the indicator of the construct (in this case responses to the questionnaire). One uses the responses of the questionnaire to infer the level of localization ability or disability. Claiming construct validity implies that there is a very clear expectation of the results with a given population. To carry out a validity study, one must compare the results of a measure to the results of a gold standard measure or have a definite pre-knowledge of what the results should be on a given measure. By definition a group of individuals with unilateral hearing impairment should have localization difficulty because of a complete inability to take advantage of the interaural timing differences (ITD) and interaural intensity differences (IID) that provide cues for localization to those with normal bilateral hearing. Therefore individuals with unilateral hearing impairment can be expected to be identified as having problems by a measure of localization abilities. In addition, individuals with normal hearing in both ears should be identified as not having localization impairment by a scale designed to identify this problem. If one can show that responses on the scale have a strong correlation with the actual ability to localize, then construct validity will have been established. In this case, a valid scale of localization impairment should clearly discriminate between these two populations.

As stated, the purpose of the pre-experiment was to establish the internal consistency reliability, test/retest reliability, and construct validity of Sections I and II of the questionnaire. The evaluation of the internal consistency reliability of Section I will serve as a replication.

3.2. METHODS

3.2.1. Test Materials

The questionnaire uses a four-option forced-choice response method. The options for each item include, “almost always”, “often”, “sometimes”, and “almost never”. Each response is assigned a number from one to four. A response is obtained for each item and a four always represents the least amount of difficulty. See Appendix E for a copy of the questionnaire.

3.2.2. Subjects

A total of fifty adult subjects with severe-to-profound unilateral sensorineural hearing loss (n=20), mild-to-moderate bilateral sensorineural hearing loss (n=10), or normal hearing (n=20) participated in the validity, internal consistency, and/or test-retest reliability investigations. See Appendix F - Table 4 for subject characteristics.

3.2.2.1. Validity

A power analysis was used to determine the appropriate number of participants per group (N = 20) for the validity portion of the study. A moderate effect size, a desired power of 0.80, and an alpha of 0.05 were assumed (Glass & Hopkins, 1996). This effect size was reasonable given the variability and the size of the effects observed in previous studies utilizing this questionnaire (Noble et al., 1995).

Forty total individuals (twenty per group), age 18 or older participated in the validity portion of the study. Twenty participants (9 males, 11 females; age range: 25-78 years; mean age: 49.65 years) presented with severe/profound sensorineural unilateral hearing impairment (defined here as pure tone average [500, 1000, and 2000 Hz] air conduction thresholds ≥ 70 dB HL in one ear). The average, impaired ear PTA for these participants was 80.91 dB HL. The range of PTAs was from 70 dB HL to beyond the stimulus limits of the audiometer (patients did not respond to the loudest stimuli presented). Twelve (60%) of the individuals in this group were impaired in their right ear, and 8 (40%) in their left. These participants also presented with normal hearing (defined here as thresholds less than or equal to 20 dB HL at all frequencies tested [250 - 8000 Hz]) in the opposite ear. See Appendix G - Figure 2 for an average audiogram for the group with unilateral hearing impairment. Among the etiology of hearing loss for this group was acoustic neuroma (n=2), childhood illness/high fever (n=3), Meniere's disease (n=2), and head trauma (n=1). Etiology was unknown for 12 subjects, 7 of whom experienced sudden hearing loss where radiographic imaging studies were negative. The average duration of hearing loss for this group was 13.68 years (duration range = 1 to 53 years).

Twenty additional participants (4 males (20%), 16 females (80%); age range: 21-32 years; mean age: 24.45 years) presented with normal hearing in both ears (defined here as thresholds less than or equal to 20 dB HL at all frequencies tested [250-8000 Hz]). See Appendix H - Figure 3 for an average audiogram for the group with normal hearing.

3.2.2.2. Internal Consistency Reliability

Because this measure is likely to be used with individuals with hearing impairment, it was felt that those participating in the evaluation of internal consistency reliability should have hearing impairment. The twenty above described participants with unilateral hearing impairment plus ten additional participants (6 males (60%), 4 females (40%); age range: 23-73 years; mean age: 48 years) with bilateral sensorineural hearing impairment (defined here as at least one air conduction threshold in each ear greater than 20 dB HL at any frequency tested [250-8000 Hz]) participated in the internal consistency reliability portion of the experiment (total N=30). A sample size of 30 participants is acceptable for a correlational study with a moderate effect size (Gay, 1992).

The average PTA for the ten additional participants with bilateral hearing impairment who were needed to complete the internal consistency and test/retest reliability portions of the study was 35.83 dB HL. The range of PTAs was from 5.83 dB HL to 75.83 dB HL. See Appendix I - Figure 4 for an average audiogram for the subgroup with bilateral hearing impairment. All of these individuals reported gradual hearing loss over time. The average duration of hearing loss for this group was 15.33 years (duration range = 5-20 years).

3.2.2.3. Test/Retest Reliability

The thirty above described participants with hearing impairment also participated in the test/retest reliability portion of the study. A sample size of 30 participants is acceptable for a correlational study with a moderate effect size (Gay, 1992).

3.3. PROCEDURES

Standard audiometric procedures were used to obtain hearing thresholds and confirm eligibility through air conduction between 250-8000 Hz and bone conduction between 500 – 4000 Hz (ANSI S3.6 – 1978 [R 1997]).

Once an individual met the eligibility requirements as described for each group above, they were asked to complete Sections I and II of the questionnaire.

The thirty participants with hearing impairment were asked to complete Sections I and II of the questionnaire a second time, three weeks after their first completion. This was considered adequate time between administrations so that individuals would not be able to remember the answers they gave for specific items.

3.3.1. Statistical Considerations

3.3.1.1. Internal Consistency Reliability

The items in each section, responded to by the thirty participants with hearing impairment, were compared to determine if each section addresses a specific premise and if the questions within each section are similar in type as they relate to that topic. Cronbach's alpha correlational analyses were applied; a correlation of ≥ 0.80 was necessary to establish internal consistency reliability (Nitko, 2001).

3.3.1.2. Test/Retest Reliability

The total scores in each section for the thirty participants with hearing impairment, over two occasions, were compared to determine the consistency of responses from one trial to the next. Pearson's correlational analyses were applied; a correlation of ≥ 0.70 was necessary to establish test/retest reliability (Nitko, 2001).

Additionally, interclass correlations were performed to determine the agreement of responses from one trial to the next.

3.3.1.3. Validity

One-tailed t-tests using mean total scores for each section of the questionnaire were performed to determine the validity of Sections I and II.

3.4. RESULTS

3.4.1. Internal Consistency Reliability

The items in each section, responded to by thirty participants with hearing impairment, were compared to determine if each section addresses a specific premise and if the questions within each section are similar in type as they relate to that topic. A priori, a correlation of ≥ 0.80 was determined to be necessary to establish internal consistency reliability (Nitko, 2001). Cronbach's alpha correlational analyses revealed internal consistency reliability of 0.90 for the disability section and 0.80 for the handicap section.

3.4.2. Test/Retest Reliability

The total scores in each section for thirty participants with hearing impairment, over two occasions, were compared to determine the consistency of responses from one trial to the next. A priori, a correlation of ≥ 0.70 was determined to be necessary to establish test/retest reliability (Nitko, 2001). Pearson's correlational analyses revealed test-retest reliability for Section I (Disabilities) at 0.90 and for Section II (Handicaps) at 0.70. Both correlations are significant ($p \leq 0.05$). Additionally, interclass correlations were performed to determine the agreement of responses from one trial to the next. The interclass correlation coefficient for Section I (Disabilities) was 0.90 and for Section II (Handicaps) was 0.70. Both correlations are significant ($p \leq 0.05$).

3.4.3. Validity

One-tailed t-tests using mean total scores for each section of the questionnaire were used to determine the validity of Sections I and II.

Questions 1-14 make up Section I (disabilities) of the questionnaire. Because participants chose an answer from a scale of 1-4 for each question, total disability section scores could range from 14-56, where a higher score would indicate less disability. The mean total disability section score was 27.6 for the group with unilateral impairment and 49.5 for the group with normal hearing. A one-tailed t-test revealed significant differences between groups ($t=10.55$, $df = 38$, $p \leq 0.05$).

Questions 15-25 make up Section II (handicaps) of the questionnaire. However, questions 22 and 25 were eliminated from analyses because they require the participant to have experience with hearing aids in order to be completed. None of the participants in this experiment had hearing aid experience. Therefore, there were 9 questions in this section. Because participants chose an answer from a scale of 1-4 for each question, total handicap section scores could range from 9-36, where a higher score would indicate less handicap. The mean total handicap section response was 28.5 for the group with unilateral impairment and 32.4 for the group with normal hearing. A two-tailed t-test revealed significant differences between groups ($t=2.90$, $df = 38$, $p \leq 0.05$). See Appendix J - Figure 5 for a graphic representation of these comparisons.

3.5. DISCUSSION

3.5.1. Internal Consistency Reliability

Cronbach's alpha examines the covariance of all possible pairs on a given scale and computes the correlation between them. A strong interrelationship was found among the items on the disabilities section (0.90) and among the items on the handicaps section (0.80). For Section I, these results compare well with those previously reported (0.93) (Flamme, 2001). Based on these measures, it can be said with confidence that each section of this measure examines a specific construct and that the questions within each section are similar in type as they relate to that construct.

3.5.2. Test-Retest Reliability

Unfortunately, one can not control for the experiences, mood, etc. of individual participants on any given occasion; nor can one account for how much memory a subject may have of their responses at completion number one when they complete the measure at visit two. It was believed that the period of three weeks was enough time that it was unlikely that the subjects could remember their responses to individual items on the measure. In the pre-experiment, participant responses from administration one versus administration two correlate positively and show good agreement. No correlations appear to be due to chance. Therefore the temporal stability of this scale has been established. This is a good tool to use if one means to apply it on multiple occasions to, for example, evaluate the impact of wearing various types of hearing aid technology on self-perceived localization disabilities and handicaps.

3.5.3. Validity

Though it is a challenge to establish the validity of a subjective measure, in the pre-experiment, a group likely to suffer from a specific disability based on their type and degree of impairment could be identified and their responses could be compared with those of a group who is unlikely to suffer from those same disabilities. The results of this analysis support that this measure allows for a valid assessment of a participant’s self-perceived localization disabilities. Also, though those same participants were not necessarily expected to suffer from handicaps related to those disabilities, this measure does appear to allow an accurate assessment of such handicaps if they do exist. Thereby, the construct validity of this scale has been established.

3.6. CONCLUSION

The results of this investigation lend further support to confidently using the Noble et al., (1995) questionnaire to obtain a valid and consistent assessment of a participant's self-perceived localization disabilities and handicaps related to those disabilities. We also can conclude that the questionnaire is a reliable measure and is just as likely to produce valid and consistent results at one administration as it is to do so at a subsequent administration.

4. MAIN EXPERIMENT

4.1. RESEARCH QUESTIONS AND HYPOTHESES

This experiment was designed to answer the following research questions. Does a significant difference exist between the self-perceived localization disabilities and/or handicaps associated with decreased ability to localize for,

1) A group of unaided individuals and that same group after listening in an omni-directional, amplified environment?

2) A group of unaided individuals and that same group after listening in a directionally enhanced, amplified environment?

3) A group of unaided individuals and that same group after wearing toggle-switch equipped hearing aids where the user has the freedom to choose the directional properties of the amplified environment?

4) A group that listens in an omni-directional, amplified environment and a group that listens in a directionally enhanced, amplified environment?

5) A group that listens in a directionally enhanced, amplified environment and a group that has the freedom to choose the directional properties of the amplified environment?

Hypotheses included:

1) The unaided group would have more self-perceived disabilities and handicaps associated with localization impairment than each of the amplified groups.

2) Being forced into directional listening at all times would cause greater problems with localization and as such this group was expected to have more self-perceived disabilities and handicaps associated with localization impairment than the group listening in an omni-directional, amplified environment.

3) The flexibility associated with being able to choose the directional setting of the listening environment, based on the communication setting, would eliminate any self-assessed localization disabilities and handicaps evidenced by individuals who listened only in a directionally enhanced, amplified environment.

4.2. METHODS

4.2.1. Research Design and Test Materials

This was an experimental study that employed both within and between groups comparisons. As noted, the outcome measures were responses to a questionnaire developed by Noble et al., (1995) which uses a four option forced choice response method, each response is assigned a number from one to four, and a four always represents the least amount of difficulty. Recall that this questionnaire consists of items divided into sections. Section I explores self-perceived disabilities (as defined by the World Health Organization [WHO], 1980) associated with decreased localization abilities. Section II allows quantification of self-perceived handicap (as defined by the WHO, 1980) directly attributable to localization disability. Results of work by Noble et al, (1995) indicate that those who perceive themselves to be disabled in terms of localization also experience handicaps that impact their quality of life because of this specific disability. This questionnaire appears to be an appropriate tool to investigate self-perceived disabilities and handicaps, associated with impaired localization, among individuals with hearing impairment.

4.2.2. Subjects

Fifty-seven 60-75 year old subjects with moderate, symmetrical, bilateral sensorineural hearing loss participated. See Appendix K – Table 5 for subject characteristics.

A power analysis was used to determine the appropriate number of subjects assuming a medium effect size, a desired power of 0.80, and an alpha of 0.05. This effect size was reasonable given the variability and the size of the effects observed in previous studies using this questionnaire (Noble, et al., 1995). There were four experimental groups.

4.2.2.1. Unaided Group

The unaided group was made up of fifty-seven participants. These participants (38 males, 19 females; age range: 60-75 years; mean age: 66.6 years) presented with moderate, symmetrical, bilateral sensorineural hearing loss and no prior hearing aid experience. Thresholds at 250-500 Hz did not exceed 40 dB HL. Thresholds were between 0-60 dB HL at 1000 and 2000 Hz, and were no worse than 70 dB HL at frequencies from 3000 Hz and above. The average PTA for this group was 31.97 dB HL. The range of PTAs was from 6.67 dB HL to 55.83 dB HL. See Appendix L - Figure 6 for the unaided group's average audiogram.

The acceptable range of hearing loss was dictated by the amount of hearing loss expected to make at least high-frequency sound inaudible yet not so much hearing loss that sound could not be made audible through amplification. The degree of hearing loss was dictated so as to ensure that audibility could be provided with amplification. At higher frequencies (shorter wavelengths), phase differences may correspond with several positions for the source of the sound; for localization, greater weight is given to intensity cues at frequencies above 800 Hz (Kietz, 1957). Audibility is essential for parsing intensity cues in localization. Additionally, audibility at frequencies $\geq$ 4000 Hz is important for identifying whether the sound source emanates from the front or rear quadrant of the horizontal plane (Musicant and Butler, 1984). However, audibility of sounds below 4000 Hz is equally important to the subjects' localization abilities.

These criteria also allowed high-frequency sloping configuration to the hearing losses. Noble et al., (1998) obtained contrast measures that show that the greater the contrast in low versus high frequency thresholds, the greater the localization accuracy.

Other audiometric criteria included that an air-bone gap of no more than 10 dB at any frequency tested (500-4000 Hz) was accepted. This allowed for all participants to present with hearing loss that was sensorineural in nature. Various experiments have been done to quantify any correlation between hearing loss and localization abilities. While in many studies the results are not robust, the general statement can be made that localization is impaired to a degree in individuals with hearing loss regardless of type or configuration (Bosatra & Russolo, 1976; Groen, 1969; Hawkins & Wightman, 1980; Jongkees & van der Veer, 1957; Nilsson & Liden, 1976; Nordlund, 1964; Rosenhall, 1985; Roser, 1966; Shitara et al., 1965; Tonning, 1973). However, it lends greater control to the investigation to have all participants present with the same type and configuration of hearing loss. Additionally, it is traditionally individuals with sensorineural hearing loss who experience psychoacoustic problems beyond audibility and this is the group for whom directional microphone technology is recommended.

Also, no more than a 15 dB disparity between thresholds at any frequency tested (250-8000 Hz) was allowed between the two ears. This criterion allowed symmetry of the hearing losses as an asymmetry or unilateral hearing loss may impact an individual's localization abilities and confound the results obtained from the questionnaire (Bronkhorst & Plomp, 1989; Colburn & Hausler, 1981; Plomp & Mimpen, 1981).

Recall that the age range of the participants was 60-75 years. Poorer localization ability can be expected with increasing age (Cranford et al., 1990, 1993; Gelfand et al., 1988; Grose et al., 1994; Grose, 1996; Pichora-Fuller &Shneider, 1991; Tonning, 1973, 1975; Viehweg & Cambell, 1960). In all of the above-cited studies it was noted that a group of elderly subjects performed more poorly than did groups of young adult subjects. While the age ranges for the elderly groups differed among the experiments, no subject was younger than 60 years of age. Again, in order to lend greater control to the experiment, all subjects who participated in the main experiment were at least 60 years old. The majority of hearing aid users continue to be older adults and this is the population of interest in this study.

The maximum age for participants was 75 years. It has been shown that older adults have difficulties with the auditory processing of speech (Birren, Woods, & Williams, 1980; Gates & Cooper, 1991; Harbert, Young, & Menduke, 1966; Jerger, Jerger, Oliver, & Pirozzolo, 1989a; Jerger, Stach, Pruitt, Harper, & Kirby, 1989b; Jerger, Jerger, & Pirozzolo, 1991; Jerger, 1992; Konkle, Beasley, & Bess, 1977; Letowski & Poch, 1995; McCroskey & Kasten, 1982; Otto & McCandless, 1982; Pestalozza, & Shore, 1955; Schmitt, 1983; Stach, Jerger, & Fleming, 1985; Stach, Spretnjak, & Jerger, 1990). Further study has shown that loss in hearing sensitivity alone does not seem to explain these difficulties (Otto & McCandless, 1982; Pestalozza & Shore, 1955). Many of the above-cited studies have revealed that central decline among the aging population better explains these problems. The group of studies looked at “older” individuals throughout the age range of 50-90 years. Stach et al., (1985) performed a longitudinal case study on an individual at ages 70, 75, 76, and 79 years. They showed central decline over this nine year period with a significant change between the 70 and 79 year assessments. Otto and McCandless (1982) examined groups of “elderly” subjects in the age ranges of 60-64 years, 65-69 years, 70-74 years, 75-79 years, and 80-84 years. The data reveal very gradual decline in Synthetic Sentence Identification (SSI) performance between age groups 60-64, 65-69, and 70-74 years. This decline appears more significant between the 70-74 year old group compared with the 75-79 year old group and is much more steep between the 75-79 year old group and the 80-84 year old group. Jerger (1992) also examined SSI performance among different age groups (50-65, 66-70, 71-75, and 76-90) and found a significant decline between the 76-90 year old group’s performance when compared with that of the 50-65 year old group and the 66-70 year old group. Finally, Schmitt (1983) worked with a “young old” group (aged 65-74 years) and an “old old” group (aged 75-84 years) and found that the “old old” group had significantly poorer time compressed speech performance than their younger counterparts.

Given the above evidence, it appears that central decline progresses somewhat gradually from the fifth decade on. This decline appears to become more steeply sloping at around age 75 years. Therefore, the age group for this experiment was limited to 60-75 years.

Two other exclusion criteria were applied. All participants were free of any documented brain injuries, because of the impact that this type of insult may have had on their responses to the questionnaire.

Given the nature of the questions on the survey, it was important that the subjects participate in activities that allowed them to complete the questions on the outcome measure.

Therefore, the Social Disengagement Index (SDI) (Bassuk, Glass, & Berkman, 1999) was administered. See Appendix M for a copy of this scale. With this scale, a composite SDI can be obtained which is based on six social constructs; 1) Spouse, 2) Visual, 3) Non-visual, 4) Church, 5) Groups, and 6) Social activities. Questions on the scale fall under one of these six constructs. Based on the subject's responses to the questions they receive either a "one" or a "zero" for each of the six constructs; a score of "one" corresponds to one social "tie" for a total of six possible social "ties". A description of how to score one social tie for each construct follows. <u>Spouse</u> – The person must currently be married. <u>Visual</u> – The subject must have visual contact with at least three relatives or friends every month. <u>Non-visual</u> – The subject must have non-visual contact with at least ten friends or relatives several times per year. <u>Church</u> – The individual must attend religious services at least one time per month. <u>Groups</u> – The subject must participate in some community group activity. <u>Social Activities</u> – The respondent must participate "sometimes" in six, or "often" in at least three of the following activities every month; shopping, dining out/going to movies or sporting events, taking day or overnight trips, volunteer work, paid community work, or regularly play cards, games, or bingo.

The tester can then determine the subject's composite SDI as follows: Five-to-six social ties equals an SDI of "one", three-to-four social ties equals an SDI of "two", one-to-two social ties equals an SDI of "three", and zero social ties equals an SDI of "four". The more social "ties" one scores, the more socially engaged is the subject.

While the measure was completed by each participant in its entirety, because the purpose of administering this scale was to determine if the subject participated in outside activities, a score of "one social tie" on the social activities construct was accepted for inclusion in the present investigation.

4.2.2.2. Aided Groups

Each of the fifty-seven subjects from the unaided group was randomly assigned to participate in one of three aided groups of nineteen subjects each, where they were fit binaurally with Siemen's custom, in-the-ear style, MUSIC hearing aids equipped with a Voice-microphone. The Voice-microphone allows the hearing aid to function with directional properties. For one group (the omni-directional only group), the hearing aids functioned only in the omni-directional mode for the duration of the investigation. For the second group (the directional-only group), the hearing aids functioned only in the directional mode for the duration of the investigation. For the final group (the toggle-switch equipped group), a toggle-switch allowed the user to switch between both modes (omni-directional versus directional).

Omni-directional Only Group - This group of nineteen individuals included 15 males and 4 females (age range: 60 – 75 years; average age: 65.95 years). The average PTA for this subgroup was 32.54 dB HL (range 15.83 – 55.83 db HL). See Appendix N - Figure 7 for the average audiogram for this subgroup.

Directional-only Group - This group of nineteen individuals included 11 males and 8 females (age range: 60 – 75 years; average age: 66.47 years). The average PTA for this subgroup was 32.85 dB HL (range 14.17 – 50 dB HL). See Appendix O - Figure 8 for the average audiogram for this subgroup.

Toggle-switch Group - This group of nineteen individuals included 12 males and 7 females (age range: 60 – 75 years; average age: 67.42 years). The average PTA for this subgroup was 32.54 dB HL (range 15.83 – 55.83 dB HL). See Appendix P - Figure 9 for the average audiogram for this subgroup.

4.3. PROCEDURES

4.3.1. Session One - Unaided participation

Unaided participation was completed with each participant at session one. Standard audiometric procedures were used to obtain thresholds and confirm eligibility through air conduction between 250 – 8000 Hz and bone conduction between 500 – 4000 Hz (ANSI, S3.6 – 1978 [R 1997]). During the hearing evaluation, uncomfortable loudness level (UCL) measurements also were taken to allow confirmation that the hearing aids that were later fit provided amplification that did not allow sounds to exceed the UCL. UCL tests were administered at each frequency from 500-4000 Hz (Jesteadt, 1980). Subjects were given a copy of the categories for loudness for the Contour Test of Loudness Perception (Cox, Alexander, Taylor, & Gray, 1997). See Appendix Q for a copy of the categories for loudness ratings. Subjects were instructed that they would hear tones of fairly high volume and that after each tone they should decide into which category of loudness the tone fit. The decibel level corresponding to a rating of "7 – uncomfortably loud" was taken as the UCL for each frequency. To further confirm eligibility, the aforementioned SDI was administered. Each participant was then asked to complete sections I and II of the questionnaire prior to being fit with amplification. Everyone was read the following instructions:

> "Now I would like you to complete the following questionnaire. Each of the questions on Section I requires you to imagine yourself in a specific listening situation and determine how often the statement is true as it relates to you. Please choose one of the four options below each question. Be sure to read the choices carefully after each question as the order for the choices will change

> depending on the wording of the question. For Section II the questions are about how you feel and/or respond in various listening situations. The response options for this section are the same as for Section I. Again, please read the response options after each question. Do you have any questions?"

When recruited for participation, each subject was informed that they would be randomly assigned to participate in either; a) one group who would use hearing aids with microphones that amplified sounds from all directions by the same amount, b) one group who would use hearing aids with microphones that applied more amplification to the sounds that come from in front of the listener than to those sounds that come from other angles, or c) one group who would have both types of microphones available for use and a toggle-switch for choosing the microphone setting. They also were informed that in order to give every participant an opportunity to experience both types of microphones, the toggle-switch type instrument would be available for use and purchase `after the experiment was complete and that currently there exists no evidence to suggest which of the three microphone configurations is best.

Finally, earmold impressions were taken and two Siemen's custom, in-the-ear style, MUSIC hearing aids were ordered. Prior to session two, each hearing aid was programmed using Siemen's Connexx software. The users' thresholds and UCLs were input and the "First Fit" program was applied.

4.3.2. Session Two

4.3.2.1. Hearing Aid Fitting – All participants

Session two was scheduled to occur when the hearing aids arrived, approximately two weeks after session one. Each participant was fitted binaurally with Siemen's custom, in-the-ear style, MUSIC hearing aids equipped with a Voice-microphone. The Voice-microphone allows the hearing aid to function with directional properties. The MUSIC circuit is a two-channel, wide-dynamic-range compression (WDRC) circuit. The use of two channels allowed the frequency and gain characteristics of low frequency versus high frequency inputs to be manipulated independently. The use of a low compression threshold allowed restoration of audibility to soft sounds while spreading the normal range of input intensities associated with signals in the environment across the individual's residual hearing area. The Voice-microphone directional microphone output can be internally equalized to produce the same frequency response as the omni-directional setting. Therefore, any differences between groups can be attributed solely to directionality. Additionally, an analysis of covariance (ANCOVA), using the responses of these subjects to the questionnaire under the unaided condition as the covariate, was performed for comparisons involving these groups. This was done to ensure that the randomization procedure used to determine assignment to each group did not by chance create a bias for any one subgroup.

For the omni-directional only group, the Voice-microphone was not enabled and no toggle-switch was available. For the directional-only group, the Voice-microphone was enabled, and no toggle-switch was available. For the toggle-switch group, both types of microphones were available and a toggle-switch on the face plate allowed users to choose which microphone to use in any given listening situation.

Upon arrival, each participant was oriented to their hearing aids. Among the points covered were:

- Battery use, insertion, and removal.
- Faceplate component orientation, use, and care including;
- Battery door
- Toggle-switch (where applicable)
- Microphone ports
- Tele-coil
- Volume control
- Cleaning and Care advice
- Instrument orientation, insertion, and removal

Each participant's ability to insert/remove the batteries and hearing aids correctly was confirmed; as was proper manipulation of the volume control, tele-coil switch, and microphone toggle-switch (where applicable).

Next, real ear probe microphone measurements were performed in order to ensure that the hearing aids were providing amplification that allowed soft (50 dB SPL), moderate (70 dB SPL), and loud (90 dB SPL) sounds to be both audible and comfortable across frequencies (500 Hz – 4000 Hz). High frequency information is important for localization and the capabilities of hearing aids begin to decline around 4000 Hz. Therefore it was important to rule out a lack of audibility as the potential cause of any localization disabilities. Using a Fonix FP40 Hearing Aid Analyzer real-ear probe microphone system, frequency-swept signals were delivered via a loud speaker positioned at zero degrees and one meter from the listener at 50, 70, and 90 dB SPL. The subject was seated with a probe microphone inserted into the ear canal and their hearing aids in place and set to user volume. The output of the hearing aids was recorded from the probe microphone, in sound pressure levels present in the ear canal while the signals were played. These sound pressure levels were required to exceed threshold (determined through previous threshold testing and converted to SPL using average transforms) but be below UCL at each frequency from 500-4000 Hz. Thereafter, the hearing aid parameters (overall gain, cross-over frequency, low channel compression ratio and knee point, and high channel compression ratio and knee point) were manipulated until audibility and comfort of soft (50 dB SPL), moderate (70 dB SPL), and loud (90 dB SPL) sounds at 500 – 4000 Hz was confirmed.

4.3.2.2. Hearing Aid Fitting - Participants with directional microphone capabilities

Specifications for the Voice-Mic system report a directivity index (DI) of 5.3 dB. Recall that the DI represents the ratio in dB of the microphone's output for signals from the front to sound originating from all directions. Ricketts (2000a) sought to quantify directivity in both omni-directional and directional hearing aids as a function of venting configuration and microphone port angle. He found that when comparing the directivity of the open ear of a Knowles Electronics Manikin for Auditory Research (KEMAR) with that found with omni-directional amplification coupled to the ear with four different levels of venting (closed, 1mm, 2mm, and open), the directivity provided by the open ear was superior. This result illustrates that the placement of the omni-directional microphone cancels out the natural directivity provided by the ear canal and pinna. Conversely, at both 500 and 1000 Hz, significant improvement in directivity was noted when no venting was allowed versus more open levels of venting. Mueller and Wesselkamp (1999) obtained similar results for in-the-ear (ITE) style hearing aids. These results combined with the finding of a significant effect of microphone port orientation suggest that manufacturer specifications may not provide the most accurate index of actual performance for a directional microphone instrument. Also it is recommended that for maximum directivity, no venting be used with directional microphone instruments. Therefore, the directional properties of the hearing aids were verified for each set of hearing aids, worn by each individual, by obtaining front-to-angle ratios (FARs). The FAR is the advantage in microphone sensitivity measured in decibels for sounds that originate from directly in front of the listener over sounds originating from other angles of incidence. Also, based on the results of the above-cited authors, no venting was allowed in any of the hearing aids.

For this experiment, FARs were obtained by subtracting the output of the hearing aid at 90°, 135°, 180°, 225°, and 270° from that obtained from signals presented at 0° azimuth. Individuals were seated one meter from a loud speaker placed at 0° azimuth. A probe microphone was seated in the ear canal and the hearing aid was in place. Female-talker, connected discourse was played from the speaker at 70 dB SPL. Using the Virtual model 340 real-ear probe microphone system, the sound pressure level (RMS) present in the ear canal was measured. The loud speaker was then positioned at one meter from the listener at each of the above noted azimuths. At each azimuth the rms SPL value from the probe microphone seated in the ear canal was recorded. FARs were calculated by subtracting the output of the hearing aid at 90°, 135°, 180°, 225°, and 270° from that obtained when the signal was presented at 0° azimuth. Killion et al., (1998) found that for every decibel of signal-to-noise ratio (SNR) improvement, an increase of approximately 9% can be obtained for scores for words-in-sentences on the Speech in Noise (SIN) test. Subjects who participated in Killion et al's experiment experienced a 20-60% improvement on word scores using directional microphones in different reverberant environments where SNR advantages of 3-8 dB were obtained. The hearing aids used in the present investigation were required to evidence FARs of at least 3 dB at each angle of incidence tested. This allowed the assumption of the potential for at least a 20% improvement in word recognition abilities when using the directional microphone versus when using the instrument in the omni-directional setting. See Appendix R - Table 6 for average FARs at each azimuth for each subgroup with directional microphone capabilities at the hearing aid fitting session.

All participants were then encouraged to wear the hearing aids full-time in a variety of day-to-day listening situations for a period of three months. They also were encouraged to call if any problems arose. Nine subjects (three from the omni-directional microphone only group, two from the directional microphone only group, and four from the toggle-switch equipped group) returned with problems that required adjustments to be made to the hearing aid parameters. Depending on the complaint, overall gain, cross-over frequency, low channel compression ratio and/or knee point, and high channel compression ratio and/or knee point were adjusted to address the problem. Once manipulation was complete, the real ear probe microphone measurements described earlier were performed to ensure that the hearing aids still provided audibility and comfort for soft, moderate, and loud sounds at 500-4000 Hz. The three month experimental wearing period began again for these nine individuals on the day that the adjustments were made.

4.3.3. Session Three – Three months post-fitting participation

At session three, each subject was asked to complete Sections I and II of the questionnaire. For those with directional microphone capabilities, the FAR measurements were repeated to ensure that the hearing aids were still functioning with at least a 3 dB directional benefit at each azimuth. See Appendix S - Table 7 for average FARs at each azimuth for each subgroup with directional microphone capabilities post hearing aid use.

All subjects were then asked to decide if they wished to purchase the hearing aids at a significantly reduced cost. Subjects were aware of this option at the beginning of the study and that they also were under no obligation. Therefore this benefit was not expected to bias these subjects. When subjects from the directional-only or omni-directional only group opted to purchase their hearing aids, the toggle switch option was added and enabled at that time. A total of 25 participants (44%) opted to purchase either one or both of their hearing aids; ten (40%) from the omni-directional microphone only group, eight (32%) from the directional-microphone only group, and seven (28%) from the toggle-switch equipped group. Based on trends from other research projects completed in conjunction with Siemens Hearing Instruments, it was anticipated that approximately 50% of the participants would purchase their hearing aids. Our finding of 44% does not deviate much from this anticipation. Also, there does not appear to have been a significant bias for any one subgroup's participants to purchase their instruments.

4.4. STATISTICAL CONSIDERATIONS

Group mean total scores from items 1 through 9 from Section I of the questionnaire were used to establish the amount of disability for discrimination of the location of sounds for each group. From Section II, group mean total scores from items 17 and 18 were used to reveal limitations on independent activity. In order to answer the research questions, a separate series of 5 comparisons each was performed for the disability and handicap defined above. Typically, when multiple comparisons are performed, the Dunn method (Glass & Hopkins, 1996) can be used to control the Type I error rate. This method requires all comparisons to be planned and the set of comparisons is defined as the unit for the Type I error rate. Thus, the overall alpha level of 0.05 is divided by the number of contrasts to be conducted. In this case alpha = 0.05/5 or 0.01. The decision to apply the Dunn method should be based on the consequences of generating a Type I error versus those of generating a Type II error. The possible outcomes for each of the five proposed research questions were reviewed as well as the actions that would be taken given each outcome. Subsequently, the actions taken in light of a Type I error were compared with those taken in light of a Type II error. The degree of erroneous actions ranged from providing the user with unnecessary precautions in counseling (Type I error) to placing the user in a potentially unsafe environment (Type II error). Other erroneous consequences included the subject not having the benefit of wearing directional microphone or toggle-switch technology (Type I error) and not providing necessary precautions in counseling (Type II error). See Appendix T - Table 8. Because the most serious erroneous consequence occurs because of a Type II error (unsafe environment), but the second worst erroneous consequence occurs because of a Type I error (losing the benefit of wearing directional microphone technology), the following conclusions were made. It was determined that the alpha level would be left at p=.05 and that precautions regarding potentially unsafe environments would be made to all subjects during counseling.

The following description explains the choice of statistical analysis. Typically parametric statistics are applied to data that are generated from a ratio or interval level scale. One can assume a quantitative continuum and therefore a normal distribution. Nonparametric tests often are used when data are generated from ordinal or categorical/nominal scales where no quantitative continuum exists and one believes they are departing from the assumptions of normality. This illustrates the argument first postulated by Stevens in 1946 who asserts that consistency between the scale of measurement that generates a data set and the statistical/mathematical treatment that the data receive is necessary for interpretable results. However, a number of individuals have argued for an alternative view that implies little or no relationship between scale of measurement and analytical techniques (Anderson, 1961; Baker, Hardyck, & Petrinovich, 1966; Burke, 1953; Gaito, 1980; Jenson, 1980; Lord, 1953; Savage, 1957). Baker et al., (1966) found that t-test sampling distributions were little affected by random adjustments to the intervals between numbers. Hence, they found that ordinal transformations have little effect on interval-scale statistical tests (i.e., the tests are robust with respect to interval assumptions) (Stine, 1989). The following series of quotes support this argument further. "A reasonable statement is that the analysis of variance F test is robust to moderate departures from normality when sample sizes are reasonably large and are equal" (Winer, Brown, & Michels, 1991, p. 101). "For the fixed ANOVA model, lack of normality is not an important matter, provided the departure from normality is not of extreme form" (Neter, Wasserman, & Kutner, 1990, p. 623). "In general, an experimenter need not be concerned about moderate departures from normality provided that the populations are homogenous in form..." (Kirk, 1982, p. 75). These references refer to one way ANOVA rather than the t-test, but in the case of two groups, the t-test and one way ANOVA are equivalent.

The pre-experiment provided the opportunity to subject the data to a test of normality. The Kolmogorov-Smirnov test of normality was applied to the original responses given by the thirty hearing-impaired subjects who participated in the pre-experiment. It was found that the data do not significantly depart from the assumptions of normality (Section I, $p = 0.20$; Section II, $p = 0.18$). Also, when the assumptions for normality are met, generally parametric analysis is more powerful than nonparametric test analysis. In this case, the pre-experiment data, which likely represent the distribution of the main experiment data, do not significantly depart from the assumptions of normality.

Kirk (1982) states that "at the outset, it should be observed that for any real data some of the assumptions will always be violated. For example, the underlying populations from which samples are drawn are never exactly normally distributed with equal variances. The important question then is not whether the assumptions are violated, but rather whether violations have serious effects on the significance level and power of the F test" (p.75). For this experiment, the data were analyzed with parametric statistics given the above argument and the results of the Kolmogorov-Smirnov test of normality.

Recall the first three of five research questions to be answered by this investigation: Does a significant difference exist between the self-perceived localization disabilities and/or handicaps associated with decreased ability to localize for,

1) A group of unaided individuals and that same group after listening in an omni-directional, amplified environment?

2) A group of unaided individuals and that same group after listening in a directionally enhanced, amplified environment?

3) A group of unaided individuals and that same group after wearing toggle-switch equipped hearing aids where the user has the freedom to choose the directional properties of the amplified environment?

In order to answer these three research questions, using paired samples t-tests, the unaided group mean total scores based on responses to questions 1 through 9 from the nineteen participants assigned to each of the hearing aid groups were compared to those same nineteen participant's aided group mean total scores based again on responses to questions 1 through 9. These analyses also were applied to the mean total scores based on responses to questions 17 and 18 from the handicaps section of the questionnaire. See Appendix U - Table 9.

Recall the last two of five research questions to be answered by this investigation: Does a significant difference exist between the self-perceived localization disabilities and/or handicaps associated with decreased ability to localize for,

4) A group that listens in an omni-directional, amplified environment and a group that listens in a directionally enhanced, amplified environment?

5) A group that listens in a directionally enhanced, amplified environment and a group that has the freedom to choose the directional properties of the amplified environment?

In order to answer these two research questions, an ANCOVA was applied to the aided group mean total scores of all three aided groups for questions 1 through 9 and for questions 17 and 18 with each group's unaided group mean total scores acting as the covariate. See Appendix V - Table 10.

In order to determine if the two sections of the questionnaire were tapping into similar, identical, or completely divergent constructs, a Pearson's Correlation was applied to the mean total unaided responses of all participants from both sections.

4.5. RESULTS

4.5.1. Research Questions One through Three

Does a significant difference exist between the self-perceived localization disabilities and/or handicaps associated with decreased ability to localize for,

1) A group of unaided individuals and that same group after listening in an omni-directional, amplified environment?

2) A group of unaided individuals and that same group after listening in a directionally enhanced, amplified environment?

3) A group of unaided individuals and that same group after wearing toggle-switch equipped hearing aids where the user has the freedom to choose the directional properties of the amplified environment?

No significant differences were found between any of the groups' self perceived level of ability to tell the direction of sounds before being fit with amplification versus after having worn either:

1) omni-directional microphone only hearing aids (N = 19; p = 0.93, SD = 0.54, Standard error of the mean = 0.12)
2) directional microphone only hearing aids (N = 19; p = 0.49, SD = 0.61, Standard error of the mean = 0.14)
3) toggle-switch equipped hearing aids (N = 19; p = 0.39, SD = 0.64, Standard error of the mean = 0.15).

No significant differences were found between any of the groups' self perceived amount of withdrawal from activities of daily living (ADLs) due to inability to localize before being fit with amplification versus after having worn either:

1) omni-directional microphone only hearing aids (N = 19; $p = 0.27$, SD = 0.30, Standard error of the mean = 0.07)
2) directional microphone only hearing aids (N = 19; $p = 0.49$, SD = 0.81, Standard error of the mean = 0.19)
3) toggle-switch equipped hearing aids (N = 19; $p = 0.33$, SD = 0.11, Standard error of the mean = 0.03).

4.5.2. Research Questions Four and Five

Does a significant difference exist between the self-perceived localization disabilities and/or handicaps associated with decreased ability to localize for,

4) A group that listens in an omni-directional, amplified environment and a group that listens in a directionally enhanced, amplified environment?

5) A group that listens in a directionally enhanced, amplified environment and a group that has the freedom to choose the directional properties of the amplified environment?

No main effect differences were found for the adjusted self perceived level of ability to tell the direction of sounds ($p = 0.45$, SD = 0.57, Standard error = 0.11; df = 2).

No main effect differences were found for the adjusted self perceived amount of withdrawal from ADLs ($p = 0.61$, SD = 0.44, Standard error = 0.08; df = 2).

4.5.3. Post-hoc Analyses

In order to determine if the two sections of the questionnaire were tapping into similar, identical, or completely divergent constructs, a Pearson's Correlation was applied to the mean total unaided responses of all participants from both sections. Corresponding with expectations, this analysis revealed a moderate correlation of 0.40, illustrating that the constructs addressed by each section are similar in type but not identical.

4.6. DISCUSSION

People with sensorineural hearing impairment who seek remediation do so primarily in order to be able to communicate better, specifically when trying to understand speech in a background of noise. Therefore, hearing aids have been designed to use technology aimed chiefly at ameliorating this problem. Currently, the most promising way to meet this goal with personal amplification is through the use of directional microphones. Research in this area has shown improved performance with understanding speech-in-noise at least in the laboratory setting. Unfortunately, the amount of benefit experienced in real world listening situations has not been to the extent that might be expected from laboratory results. For example, in highly reverberant environments, the benefits of directional microphone technology can not be realized because competing messages (i.e., noise) are reflected in the frontal plane and are not attenuated as desired.

Several hypotheses have been postulated herein. The first three research questions asked if there was a significant difference in the responses of unaided individuals and of those same individuals after having worn amplification with omni-directional microphones, directional-only microphones, or hearing aids equipped with a toggle-switch. It was hypothesized that wearing any type of microphone configuration on amplification (omni-directional, directional-only, or toggle-switch equipped), fit so that all frequencies between .5 and 4 kHz were audible, would allow significant improvement in the self-perceived level of ability to tell the location of sounds and significant decrease in the level of withdrawal from activities where localization disability is potentially problematic. Recall that Noble et al., (1995) using the same questionnaire, found reports of increased localization abilities when using either one or two omni-directional only hearing aids as compared to the unaided condition. Interaural intensity cues are one of the primary indicators used to localize. Because many of the sounds that are important for localization are inaudible to the individual with moderate sensorineural hearing impairment, restoring the ability to hear these otherwise inaudible cues should allow one to localize better.

Because timing and intensity cues are among the properties that are altered with the use of directional microphone technology and are the primary determinates for successful localization, it also was hypothesized that individuals with moderate sensorineural hearing impairment, who wore only directional microphone technology, would identify a significantly lower level of ability to tell the location of sounds and greater level of withdrawal from activities where localization disability is potentially problematic, than those who wore omni-directional only amplification.

Finally, if the previous hypothesis was shown to be valid, it also was expected that those wearing toggle-switch equipped hearing aids would identify a significantly greater level of ability to tell the location of sounds and lower level of withdrawal from activities where localization disability is potentially problematic, than those wearing directional-only amplification. The toggle-switch would allow these individuals to choose to use omni-directional microphones when in settings where they found themselves having problems localizing and thus could eliminate any localization disabilities and/or anxiety associated with such.

None of these hypotheses were supported. In the case of the unaided versus aided comparisons, no significant differences between the unaided responses versus the aided responses were found. Stated differently, wearing hearing aids did not significantly increase or decrease the participants' self-perceived level of ability to tell the direction of sounds nor did it significantly increase or decrease their level of withdrawal from activities where the ability to localize is likely to be important.

The above results appear to be in direct contrast to those found by Noble et al., (1995) in that a significant difference was not noted between the responses of the unaided group and of those wearing omni-directional microphone only amplification. The likely explanation for this discrepancy lies in differences in the subject demographics between the two studies as well as the treatment of the data. The participants in the Noble et al., (1995) study differed from the present investigation's participants in three important ways:

1. The sample from the earlier investigation had a much bigger age range but, higher average age than any of the main experiment groups examined herein (average difference equals five years).
2. The average better-ear hearing threshold levels for the Noble et al. group were 4.2 – 16.2 dB nHL worse than the corresponding thresholds for the group used in the main

experiment. The four frequency average hearing level (average of the better-ear thresholds at .5, 1, 2, and 4 kHz) was 10.5 dB nHL higher for the Noble et al., (1995) participants.

3. Each of the individuals who participated in the Noble et al., (1995) investigation had previous amplification experience prior to answering the questionnaire in the "unaided" condition. This particular difference could have a profound effect on the difference between the results found in the earlier investigation versus the present investigation. Individuals who are comparing performance ability when their hearing aids are turned off versus having never worn hearing aids are likely to have a very different perception of their abilities.

Another important difference between the two investigations lies in the treatment of the data. Noble et al., (1995) state that because some respondents answered some negatively worded items as though they were positively worded, rather than try to second guess what respondents had intended, the results from negatively worded items (#2,4,7,11, and 13) were excluded from analyses. This was not the case for the present investigation. A response was obtained for each question and as the questionnaires were completed in the presence of the investigator, when any discrepancies in the theme of responses by an individual were present, the intended response of the participant was confirmed. In addition, items 10-14 were not used in the present analyses as it was determined *apriori* that only those items that revealed possible limitations on the ability to tell the location of sounds (as opposed to the distance of sounds) would be examined.

It was assumed, from the wealth of data available about the localization abilities of individuals with hearing impairment, that the participants in this investigation would have significantly more self-perceived localization disabilities and handicaps than those with normal hearing. Because the results of this experiment deviated from expectations, six t-test comparisons were performed to see if significant differences existed between the mean total scores for questions 1-9 and 17 &18, for the 20 individuals with normal hearing from the pre-experiment versus the unaided responses of the 19 subjects from each aided subgroup from the main experiment. It was found that each of the three groups of subjects with hearing impairment identified a significantly lower level of ability to tell the location of sounds than the group with normal hearing. This finding illustrates that the potential did exist for significant improvement with the use of amplification and allows us to be more certain that the results are a valid representation of the state of things and not the product of an erroneous methodology. See Appendix W – Table 11 for the data analysis. However, none of the unaided groups with hearing impairment evidenced a significant difference in level of withdrawal from activities where localization is potentially an issue than the group with normal hearing, leaving no room for significant improvement with hearing aids on this factor. Likely explanations for why the level of improvement with hearing aids was not significant for the disability factor include the following:

1. The scale uses a four-option forced choice response method. It is not an interval level scale, in that one may not assume that mathematical laws can be appropriately applied to the numbers assigned to each option. The numbers assigned to the categories simply allow the examiner to know that a lower score is equal to more disability than a higher score. The descriptors assigned to each option do follow a less-to-more-frequency pattern. It is possible that the differences from one category to the next were not precise enough to allow a significant difference to be seen. For example,

perhaps five options (whether categorical or interval) would have allowed more accurate differences to be revealed.

2. Following this line of reasoning, the true effect size, or the amount of difference in level of disability or handicap allowed by providing amplification, was shown to be quite small (See Appendix X – Table 12). *Apriori*, based on the work of Noble and colleagues (1995), the effect size was assumed to be medium. The amount of effect that amplification actually has on the scores may be too small to be meaningful as evidenced by the great number of individuals needed per group to find a significant difference given the true size of the effect in the present investigation.

3. Another theory is that perhaps this measure, which was shown to have construct validity with groups who could be expected to respond at the extremes of the scale (i.e., those with normal versus unilateral hearing impairment) is not as well suited to fettering out more moderate levels of localization disability and/or handicaps associated with impaired localization, as is quite likely the case for those with bilateral hearing impairment. For example, perhaps the situations described need to have more detail or perhaps more or different situations need to be included.

There exists the potential for the development of an interval level self-perception scale with greater numerical resolution and possibly a greater number of more descriptive localization-necessary listening situations.

4. Finally, it is possible that some other psychoacoustic factor(s) necessary for localization, other than lack of audibility of timing and intensity cues, is (are) impaired in those with hearing loss and is (are) the reason that restoring audibility through amplification is not sufficient to improve self-perceived ability to tell the

direction of sounds and subsequently reduce the amount of withdrawal from situations where the ability to localize is a factor. One potential culprit is an inability to take advantage of spatial cues. Noble and Perrett (2002) found that in parsing the auditory array, attention to spatial cues is heightened when the components of the array are confusable on other acoustic grounds; for example, when the noise and the signal are both speech signals or are both speech signals spoken by females or both spoken by males. Additionally, laboratory results also have shown that directional benefit is influenced by the amount of spatial separation between signal and noise sources (Leeuw & Dreschler, 1991; Ricketts, 2000b).

This latter theory can be expanded upon to explain why significant deterioration was not seen with directional-only amplification versus omni-directional amplification or toggle-switch equipped amplification. Rather than the directional-only microphones making the localization situation worse by confusing timing and intensity cues, none of the hearing aids overcame or addressed the factors that are impaired in the listener that were needed to re-establish normal localization ability. Again, for example, none of the hearing aids used in this investigation are designed to improve the amount of spatial separateness associated with the signal and noise. When localization abilities are impaired because of hearing loss, just like in the case of speech recognition ability, simple intensity restoration may not be enough to return performance to pre-hearing loss levels.

Although differences in the self-perceived level of localization abilities were not evidenced herein, objective measures of localization ability with directional microphone amplification have not been assessed to date. Future research should include a replication of this study using objective outcome measures of localization ability. Also, a comparison of the responses of individuals with hearing impairment with those of their significant others could yield interesting results in terms of perception.

4.7. CONCLUSION

In conclusion, it appears that hearing aids with omni-directional microphones, directional-only microphones, and those that are equipped with a toggle-switch allowing a choice of the directional properties of the instrument neither increase nor decrease the self-perceived level of ability to tell the direction of sound or the level of withdrawal from situations where localization ability is a factor. Concurrently, directional-microphone only technology does not significantly worsen or make better these factors as compared to the other two microphone configurations. Future research should include objective measures of localization ability using the same paradigm used herein. If significant differences are found with these measures, then development and administration of a scale that includes more descriptive and/or more numerous listening situations designed to fetter out level of self-perceived localization disability and associated handicaps, potentially on a more numerically resolute scale, would be warranted. As would the development of a scale for use with the individual with hearing impairment's significant other. If ultimately no significant differences in either objective or subjective measures are found, then concern over decreases in quality of life and safety with directional microphone use need no longer be considered.

APPENDIX A

FREQUENCY SELECTIVITY LITERATURE

Table 1 - Frequency Selectivity Literature

Study	Purpose	Conclusions	Limitations
Hoekstra and Ritsma, 1977 Perceptive Hearing Loss and Frequency Selectivity	To compare different psychophysical measures of frequency selectivity. Including: 1) Frequency discrimination using band filtered periodic pulse-trains, and 2) Psychophysical tuning curves (PTC).	• Were not able to find a one to-one relationship between PTCs and frequency discrimination. • Poor frequency discrimination was always accompanied by bad PTCs but not always of a consistent shape. • Bad PTCs did not always imply poor frequency discrimination. • Frequency discrimination seems to imply better frequency selectivity than would be expected on the basis of PTCs.	

Table 1 (continued)

Study	Purpose	Conclusions	Limitations
Wightman et al, 1977 **Factors influencing frequency selectivity in normal and hearing-impaired listeners.**	Comparison of both simultaneous and forward-masking tuning curves in both normally hearing and hearing impaired subjects.	• Results indicate that simultaneous masking does not provide a "pure" measure of frequency selectivity due to the influence of combination tones and "suppression". • Suggests that forward-masking is a more appropriate measure of frequency selectivity but also may not represent "true" selectivity.	• Low number of subjects.
Bonding, 1979 **Frequency selectivity and speech discrimination in sensorineural hearing loss.**	Two measures of frequency selectivity (Critical band in loudness summation and Psychophysical tuning curves) were compared with the capacity for speech discrimination in subject with sensorineural hearing loss.	• Critical bands (CB) did not correlate with the degree of hearing loss or with the speech discrimination score. • Psychophysical tuning curves (PTC) changed with increasing hearing loss as did speech discrimination scores. • There was significant correlation between speech discrimination scores and cochlear tuning as expressed by the PTCs. • The authors propose that PTCs are a more valid measure of frequency selectivity than are CBs.	• Used subjects with several different types of sensorineural hearing loss, but did not discus the potential for trends with any one type of loss (e.g. Meniere's vs. presbycusis, etc.).

Table 1 (Continued)

Study	Purpose	Conclusions	Limitations
Dreschler and Plomp, 1980 **Relation between psychophysical data and speech perception for hearing-impaired subjects, I.**	To find out what auditory properties are responsible for the reduction in speech intelligibility of listeners with hearing impairment both in quiet and background noise. Used basic audiometry, vowel discrimination tasks, and speech reception threshold (SRT) to perform a correlational analysis.	• The measures of the frequency resolving power of the ear correlate highly with the audiogram. • The SRT in noise is strongly correlated with the slope of the audiogram. • Vowel perception is distorted in hearing-impaired individuals, resulting in high F1 weighting and low F2 weighting even though hearing-impaired individuals use the same perceptual dimensions as normal hearing individuals for vowel perception.	• Used only children aged 13-18. No adult data. No consideration for child abilities with vowel perception tasks. • Used only 10 hearing-impaired subjects and only 5 normally hearing subjects.
Festen and Plomp, 1981 **Relations between auditory functions in normal hearing.**	Investigated frequency resolution, temporal resolution, and nonlinearity in normal hearing subjects.	• The bandwidth in non-simultaneous masking is about one half the band-width in simultaneous masking. • The extent of masking effects for forward and backward masking are independent of masker level. • Masking drops sharply immediately before and after the masker and more gradually at greater delays.	

Table 1 (Continued)

Study	Purpose	Conclusions	Limitations
Festen and Plomp, 1983 **Relations between auditory functions in impaired hearing.**	Investigated frequency resolution, temporal resolution, and nonlinearity in hearing impaired subjects.	• Bandwidths differ only slightly for non-simultaneous and simultaneous masking. • Broader tuning curves than for normally hearing individuals. • Slopes about twice as steep as for normally hearing individuals. • Notch near the probe frequency in PTCs for hearing – impaired subjects. • Average time constant is nearly twice that of normal hearing subjects. • Very shallow masking slopes. • A gradual decay in masking is found over the whole range of masking stimulation.	• Results are not fully comparable with those from earlier study by these authors done with normal hearing subjects. • Earlier study was not done with comparison in mind and some procedures are different.

Table 1 (Continued)

Study	Purpose	Conclusions	Limitations
Carney and Nelson, 1983 **An analysis of psychophysical tuning curves in normal and pathological ears.**	To compare simultaneous tuning curves from normal hearing and hearing impaired listeners using probe tones at similar SLs and at similar SPLs for both types of listeners.	• Influence of combination tones at high SPLs for normally hearing listeners as evidenced by discontinuities in the low-frequency region of their PTCs. • Inverted tuning curves for certain probe frequencies for hearing impaired listeners with flat losses. Broader tuning is used to explain the above finding. • Because testing was done at similar SPLs for both normal hearing and hearing impaired listeners, it now appears as though impaired ears may not be as poor at resolving simultaneous tones at high SPLs as previously thought.	• Used a very small N. No consistency to hearing losses among the subjects. This allowed for some interesting comparisons but no strong generalizations.

Table 1 (Continued)

Study	Purpose	Conclusions	Limitations
Stelmachowicz et al, 1985 **Speech perception ability and psychophysical tuning curves in hearing impaired listeners.**	To compare the findings from speech-perception ability tests performed in quiet and in the presence of broadband and low-pass filtered noise on normal and hearing-impaired listeners with various aspects of their PTCs.	• In normally hearing listeners an increase in signal-to-noise ratio (SNR) is needed to maintain 50% performance as the signal level is raised from 60 dB SPL to 80 dB SPL. • Hearing impaired exhibit poorer performance in broadband noise than normals do at 60 dB SPL. • The deviations of PTCs n hearing-impaired listeners from those of normals increase as the degree of hearing loss increases.	• Did not use individuals with severe hearing losses. • Resolving the speech waveform into constituent frequency components may not be as useful as psychophysical frequency analysis so as to preserve the relative importance of both frequency selectivity and threshold elevation in the perception of speech.

APPENDIX B

PYSCHOPHYSICAL TUNING CURVE

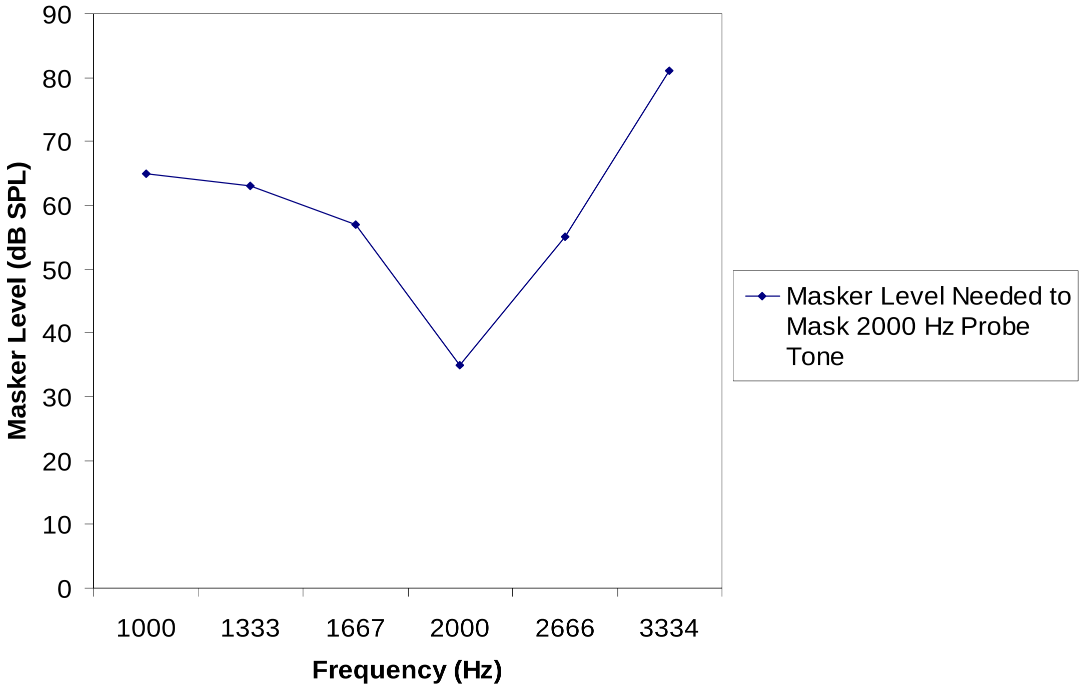

Figure 1 - Psychophysical Tuning Curve for a 2000 Hz tone from an ear with normal hearing

APPENDIX C

LOCALIZATION LITERATURE

Table 2 - Localization Literature

Study	Purpose	Conclusions	Limitations
Nilsson and Liden, 1976 Sound localization with phase audiometry.	To describe a method of phase audiometry and compare it with free-field sound localization.	• The thresholds for interaural time delay determined with phase audiometry approach those of free-field audiometry	• Questionable comparison. Do phase audiometry and free-field audiometry test the same thing? Perception of fused image is located in the heard for phase audiometry and in the room for free-field audiometry.
Hawkins and Wightman, 1980 Interaural time discrimination ability of listeners with sensorineural hearing loss (SNHL).	To investigate discrimination of interaural time differences in subjects with SNHL of various configurations.	• No apparent relationship between audiometric configuration and performance. • When the subjects with SNHL are considered as a group, their mean interaural time just noticeable differences was less than for individuals with normal hearing at two SPLs tested (30 dB SL and 85 dB SPL).	• N = 8 total. Only two subjects for each type of hearing loss.

Table 2 (continued)

Study	Purpose	Conclusions	Limitations
Rosenhall, 1985 The influence of hearing loss on directional hearing.	To study the influence of both unilateral and bilateral cochlear hearing loss on the ability to lateralize a 500 Hz tone.	• Subjects with unilateral hearing loss performed just as well as those with bilateral hearing loss. • Used same procedure as Nilsson and Liden, 1976, and these subjects with mild loss performed slightly poorer than the normals form the previous study. • At 500 Hz, patients with hearing loss no worse than 40 dB had slightly prolonged interaural time differences (ITDs). Patients with hearing loss from 45-55 dB had severely disturbed sound localization.	• Over generalized. Should have used hearing loss at other frequencies besides 500 Hz as a covariate for generalizations
Moore et al, 1990 Tracking of a "moving" fused auditory image under conditions that elicit the precedence effect.	To provide preliminary normative data regarding normal subjects' ability to track a "moving" fused auditory image.	• Subjects with neuropathology yielded results that were dramatically different qualitatively and quantitatively from those of the normal group.	

Table 2 (continued)

Study	Purpose	Conclusions	Limitations
Cranford et al, 1990 Effects of aging on the precedence effect in sound localization.	• To identify specific aging effects in the precedence effect. • To determine whether individual differences in hearing sensitivity among the elderly influenced their performance.	• Elderly exhibited poorer performance than younger group for short delays < .7 milliseconds. No significant differences for delays above .7 milliseconds. • Bimodal distribution for mean hearing loss causing influence of severity to be unclear. • Findings from elderly are similar to those seen in multiple sclerosis (MS) patients from Moore et al, 1990. Argument for the influence of demyelination on neural conduction in aging.	

Table 2 (continued)

Study	Purpose	Conclusions	Limitations
Noble at al, 1994 Effects of sound localization on configuration and type of hearing impairment	To specify the roles of degree and type of hearing loss on various aspects of auditory localization.	• Precedence effect appears at 4-5 months of age. • At five years of age performance is similar to adults for simple stimuli but worse for complex stimuli. • Eighteen month olds and five year olds perform better for single source MAA tests than for dichotic MAA tests. • Localization improves between 18 months and 5 years of age. • Basic localization may reach adult acuity by childhood but precision under conditions where precedence effect is present does not.	
Noble et al, 1997 Auditory localization, detection of spatial separateness, and speech hearing in noise by hearing impaired listeners.	To report the inter-relationships in performance on tests of localization, speech hearing in noise, and detection of spatial separateness.	• All hearing loss groups showed little or no separation benefit. • No consistent links between their ability to localize and benefit from separation.	

Table 2 (continued)

Study	Purpose	Conclusions	Limitations
Yang and Grantham, 1997 Cross-spectral and temporal factors in the precedence effect: Discrimination suppression of the lag sound in free-field.	To determine which of two hypotheses better predicts discrimination suppression of the lag stimulus in the free-field. 1) Spectral overlap 2) Localization Strength	• When the center frequencies of the lead and lag stimuli were varied, results support the spectral overlap hypothesis. Localization strength had no apparent effect on discrimination performance here. • When localization strength was manipulated as the independent variable, by varying stimulus rise times and holding center frequencies constant, results were consistent with the localization strength hypothesis. • Spectral overlap dominates in discrimination suppression in the free-field with the likely hood that localizations strength plays a secondary role.	• By manipulating rise times to vary localization strength, one can not be certain that other consequences of varying rise times besides changing localization strength were not responsible for the results. • Did not justify that varying rise times sufficiently alters localization strength.

Table 2 (continued)

Study	Purpose	Conclusions	Limitations
Noble et al, 1998 Improvements in aided sound localization with open earmolds. Observations in people with high-frequency hearing loss.	• To determine any correlation between hearing threshold level and localization abilities. • To observe the effects of open earmolds on the localization abilities of people with high-frequency hearing loss.	• Significant correlations with hearing threshold levels and performance in the horizontal and vertical planes. • Poorer hearing at high-frequencies associated with better lateral vertical localization. Better hearing at low-frequencies associated with better lateral vertical localization. • Poorer hearing at low-frequencies associated with poorer horizontal localization. • The greater the contrast between low and high frequency thresholds, the better the localization accuracy. • Aided localization restored to unaided accuracy with open earmolds. "Sleeve"-type earmolds provide limited further benefit. • Open earmolds may be associated with better speech understanding in spatially separated noise.	• When testing using patient's own closed earmolds, gain was lower than typical settings and lower than what was used in testing for qualification to participate. Due to setting VC with open molds in place and needing to adapt it for feedback control.

Table 2 (continued)

Freyman et al, 1998 Intensity discrimination for precedence effect stimuli.	• To determine whether a lead sound suppresses sensitivity to intensity changes in a lag sound. • To examine the detectibility of the lag sound compared to when the lead sound is presented in the absence of a lag sound.	• Performance was best in the control condition when both the lead and the lag changed level equally. • Data suggest that the precedence effect does not involve suppression of the intensity contribution of the lag sound. • Listeners were sensitive to the presence of a lag sound when compared to diotic stimuli. • Reflections can aid speech communication by increasing the signal level reaching the ear. • Reflected sound enhances the overall quality of complex sounds. • Intensity properties from echoes signify aspects of the physical space one is in.	• Interpretations of the data depend on the choice of analysis.

Table 2 (continued)

Study	Purpose	Conclusions	Limitations
Chiang and Freyman, 1998 The influence of broadband noise on the precedence effect.	• To quantify the influence of broadband noise on the precedence effect.	• Results consistent with the idea that the image produced by a lead sound plus a lag sound is pulled slightly toward the lag sound in the presence of noise. • For all N, the increase in the level of the lag sound needed to produce a center image was less in noise than in quiet. • For every N, noise increased the audibility of the lag, allowing it to be heard as a separate sound sooner. • The influence of the lagging sound is strengthened by the introduction of back ground noise, however, in general, the location of the fused image is still dominated by the lead sound.	

Table 2 (continued)

Study	Purpose	Conclusions	Limitations
Tollin and Henning, 1998 Some aspects of the lateralization of echoed sound in man I. The classical interaural delay based precedence effect.	• To characterize more accurately the temporal dependence of the precedence effect on inter-click interval (ICI).	• Results at average ICIs (.8 to 9.6 ms) are consistent with the notion that the lateralization of dichotic pairs is largely determined by the information carried in the lead sound. • Results at short ICIs (< .4ms) are consistent with the idea that the interaural characteristics of both the lead and the lag sounds together determine the perceived location of the composite image (summing localization). • Results at long ICIs (12.8 ms) suggest that the perceived lateral position was based on the average of the interaural time differences of the sounds. This parallels the summing localization theory.	• N = 4. Two subjects were the authors.

Table 2 (continued)

Tollin and Henning, 1999 Some aspects of the lateralization of echoed sound in man II. The role of the stimulus spectrum.	• Investigate the role of spectral cues in the lateralization of clicks.	• Results suggest that echoes that arrive within 2-3 ms of an initial sound are not suppressed but play a substantial role in lateralization through contribution to the spectral characteristics of the fused image.	• N = 3. Two subjects were the authors.

APPENDIX D

DIRECTIONAL MICROPHONE LITERATURE

Table 3 - Directional Microphone Literature

Study	Purpose	Conclusions	Limitations
Madison and Hawkins, 1983 The signal-to-noise ratio advantage of directional microphones	Obtain the signal-to-noise ratio necessary for 50% correct word recognition in different types of noise conditions with omni-directional and directional modes of a hearing aid.	• Significant improvement was offered by the directional aids in both anechoic and reverberant conditions. • The directional advantage in the anechoic condition was significantly better than in the reverberant condition.	• Only subjects with normal hearing were used. • Results are only generalizable to the specific aids used.

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Hawkins and Yacullo, 1984 Signal-to-noise ratio advantage of binaural hearing aids and directional microphones under different levels of reverberation.	Determine how reverberation, monaural versus binaural fitting, and directional versus omni-directional microphones interact.	• Advantages of binaural fitting and directional microphones are similar for subjects with normal hearing and those with hearing-impairment. • No significant differences in binaural advantage as a function of reverberation time. • The directional microphone advantage is greater than the binaural advantage. • Substantial individual differences were observed as regards susceptibility to reverberation.	

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Leeuw and Dreschler, 1991 Advantages of directional hearing aid microphones related to room acoustics.	• Determine how the directional microphone advantage is influenced by the critical distance. • Determine if directional hearing abilities are affected by directional microphones.	• Results do not allow a simple model for predicting speech reception performance as a function of critical distance. • The hearing aid with a directional microphone provides better directional hearing for low-frequency sounds as compared to an omni-directional hearing aid.	
Soede et al, 1993 Assessment of a directional microphone array for hearing-impaired listeners.	Clinical assessment of endfire and broadside microphone arrays.	• The aid with one cardiod microphone attenuates the noise field by 2.5 dB. • The broadside microphone array attenuates the noise field by 7 dB. • The endfire microphone array attenuates the noise field by 6.8 dB. • The array microphones work in a reverberant environment and they double the critical distance. • The microphone arrays significantly improve the critical signal-to-noise ratio for subjects with hearing impairment.	

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Bilsen et al, 1993 Development and assessment of 2 fixed-array microphones for use with hearing aids.	Determine any additional benefit to adding a directional (cardiod) microphone to array configurations.	• Adding cardiod microphones to arrays can give a significant improvement to the Directivity Index at low frequencies. • Combining a number of arrays to one set of eyeglasses provides an extra improvement of about 2-3 dB to the Directivity Index.	
Valente et al, 1995 Recognition of speech in noise with hearing aids using dual microphones.	Determine the benefit provided by a dual-microphone system on speech recognition in noise in a realistic noise and reverberation environment.	• Dual microphone systems provide an average improvement of 7.4 – 8.5 dB.	
Preves et al, 1999 Field trial evaluations of a switched directional/omni-directional in-the-ear hearing instrument.	Assessment of in-the-ear style hearing aid with switchable directional/omni-directional capabilities.	• The critical signal-to-noise ratio for speech recognition is better with the directional mode. • Performance is better when the directional mode frequency response is equalized to match that of the omni-directional mode.	
Wouters et al, 1999 Speech intelligibility in noise environments with one- and two-microphone aids.	Compare the effect of a dual-microphone system with an omni-directional system for the effect on speech perception in noise.	• A benefit of the directional mode over the omni-directional mode is apparent.	

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Amlani, 2001 Efficacy of directional microphone hearing aids: A meta-analytic perspective	Establish the degree of advantage provided by directional microphone hearing aids.	• When data are pooled across all variables, directional microphones are found to provide a statistically significant advantage. • High reverberation conditions have been shown to affect the directionality of directional hearing aids. • Digital signal processing when coupled with omni-directional microphones improved speech intelligibility significantly over that observed when digital was coupled with directional microphones.	
Cord et al, 2002 Performance of directional microphone hearing aids in everyday life	To determine the self-assessed use patterns and benefits of directional microphone technology in real-world situations	• Reported using the directional mode one quarter of the time on average. • Reported the same level of satisfaction with each microphone. • Patients encounter significantly more situations that favor omni-directional microphone use.	• Weak control. Telephone interview and mail solicited paper and pencil questionnaires. • No psychometric data on Microphone Performance Questionnaire.

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Ricketts and Henry, 2002 Evaluation of an adaptive, directional-microphone hearing aid	To determine the effectiveness of adaptive directional processing for improvement of speech recognition in comparison to non-adaptive directional and omni-directional processing in listening environments intended to simulate those found in the real world.	• Improved speech recognition with adaptive and non-adaptive directional processing over omni-directional processing. • In some listening environments, a significant speech recognition advantage was measured for the adaptive mode when noise was presented from the side of the listener.	• Did not equalize the frequency response between the directional and omni-directional modes. • Some results could not be easily interpreted because the non-adaptive directional pattern was not optimized.
Surr et al, 2002 Influence of environmental factors on hearing aid microphone preference	To identify characteristics of everyday listening situations that influence user preference for omni-directional versus directional hearing aid microphones.	• Participants identified and described more situations where they felt that adaptive-directional microphones performed better than omni-directional microphones. • Location of the primary talker, presence or absence and type of background noise, and type of space influenced the microphone preference.	• All participants were male. • Participants had no prior directional microphone experience. • All participants had trouble finding situations where they were able to perceive a difference between the two microphone modes. • Only adaptive directional microphones were used and therefore the results may not be very generalizable.

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Ricketts and Hornsby, 2003 Distance and reverberation effects on directional benefit	• To examine the impact of speaker-to-listener distance on directional benefit in two reverberant environments. • Compared speech transmission index (STI) measures to measured sentence recognition to determine if performance was predictable across changes in distance, reverberation and microphone modes.	• Decrease in directional benefit with increasing speaker-to-listener distance in the moderate reverberation condition. • No similar decrease in benefit was measured in the low reverberation condition. • Some directional benefit can still be obtained when listening beyond the “effective” critical distance under conditions of low to moderate reverberation. • The use of STI values for the prediction of average word recognition across various listening conditions was supported.	• May need to apply corrections for audibility in the STI calculations in order to account for the effect of the hearing aid and/or environmental factors that affect the extreme frequencies differentially.

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Ricketts et al, 2003 Full time directional versus user selectable microphone modes in hearing aids	• To examine hearing aid benefit as measured by speech recognition and self-assessment across omni-directional and directional modes. • Compare directional benefit as measured in the laboratory to wearer's perception of benefit in everyday environments across various directional modes	• Toggle-switch type hearing aid allows more self-perceived directional benefit than the omni-directional only hearing aid. Not so for directional-only versus omni-directional only. • Self-assessed directional advantage when signal comes from in front but not when signal is behind or localization is required.	• Reliability of newly proposed scales unknown.
Bentler et al, 2004 Hearing-in-noise: Comparison of listeners with normal and (aided) impaired hearing	• To evaluate two- and three-microphone directional hearing aids in both fixed and adaptive settings in a typical laboratory setting (stationary noise) and in a more realistic listening environment (moving noise).	• When the noise was stationary, both two- and three- microphone directional hearing aids allowed those with hearing impairment to perform as well as those with normal hearing. • When the noise was moving, only the three-microphone directional hearing aid set to an adaptive directional response allowed those with hearing impairment to perform as well with those with normal hearing.	

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Cord et al, 2004 Relationship between laboratory measures of directional advantage and everyday success with directional microphone hearing aids	• This investigation examined whether persons who were successful users of directional microphone hearing aids in everyday living tended to obtain a larger directional advantage in the test booth than persons who were unsuccessful users.	• Mean directional advantage did not differ significantly between patients who used the directional mode regularly and those who tended to leave their hearing aids set in the default omni-directional mode. • Success with directional microphone hearing aids in everyday living cannot be reliably predicted by the magnitude of the directional advantage obtained in the clinic.	• Determination for group assignment (i.e. successful user of directional microphone or not) was based on subjective report of the amount of time the directional mode was used; evidence suggests that individuals are not good at making this determination.

Table 3 (continued)

Study	Purpose	Conclusions	Limitations
Walden et al, 2004 Predicting hearing aid microphone preference in everyday listening	• To determine the extent to which the preferences of hearing-impaired patients for the omni-directional versus the directional mode in everyday listening situations could be predicted from the characteristics of the listening environments.	• Hearing-impaired adults typically spend the majority of their active listening time in situations with background noise present and surrounding the listener, and the signal source located in front and relatively near. • The omni-directional mode tended to be preferred in relatively quiet listening situations or, in the presence of background noise, when the signal source was relatively far away. • The directional mode tended to be preferred when background noise was present and the signal source was located in front of and relatively far away.	• All but one subject were male. • Participants had no prior directional microphone experience.

APPENDIX E

QUESTIONNAIRE FOR DISABILITIES AND HANDICAPS ASSOCIATED WITH LOCALIZATION

Section I – Localization

1. You are at home in a quiet room. There are other people in the house (friends or family). They are talking in another room and you can hear them. Can you tell which part of the house those people are in?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

2. Do you turn the wrong way when some-one that you can't see calls out to you?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

3. You are outdoors in an unfamiliar place. You can hear the sound of someone mowing a lawn. You can't see where they are. Do you know where the sound is coming from?

Almost never, 2) Sometimes, 3) Often, 4) Almost Always

4. You are sitting around a table or at a meeting with several people. There is some background noise. You can't see everyone. Do you find it hard to know which person is speaking?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

5. You are in an unfamiliar house. It is quiet. You hear a door slam. Can you tell what part of the house the sound came from?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

6. You are in a high-rise apartment or office building. You can hear sound from another floor. Can you tell whether the sound is coming from above or below you?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

7. You are standing on the footpath of a busy street. A car horn sounds. Do you have difficulty telling which direction it came from?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

8. You are outside. A dog barks loudly. Can you tell where it is without having to look?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

9. You are standing on the footpath of a busy street. Can you hear which direction a bus or truck is coming from before you see it?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

10. In the street, can you judge how far away someone is, from the sound of their voice or footsteps?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

11. You are outdoors in an unfamiliar place. Someone calls out from somewhere above you (such as a balcony or bridge). Do you find it hard to tell where the voice is coming from?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

12. You are standing on the footpath of a busy street. Can you tell, just from the sound, roughly how far away a bus or truck is?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

13. You are outside. You can hear an airplane. Do you find it hard to tell where the plane is in the sky, by the sound alone?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

14. If you have a problem telling where something is coming from, does it help if you move around to try to locate the sound?

Almost never, 2) Sometimes, 3) Often, 4) Almost Always

Section II – Handicap

15. Are you a confident person?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

16. You are in a place that is unfamiliar to you. Do you get nervous or feel uncomfortable in this situation because of trouble telling where sounds are coming from?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

17. Does difficulty telling where sounds are coming from lead you to avoid busy streets and shops?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

18. Because of difficulties telling where sounds come from, is a visit to the shops something you don't do by yourself?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

19. You are invited into a stranger's home. Do you feel less at ease in the stranger's home than in a home that is familiar to you?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

20. If you are in a busy place, such as a crowded shopping center or city street, do the sounds you hear seem all mixed up or confused?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

21. When sounds are mixed up or confused, does this cause you to feel confused or unsure about exactly where you are?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

22. Does wearing your hearing aid(s) reduce any feelings of confusion you may experience?

1) Almost never, 2) Sometimes, 3) Often, 4) Almost Always

23. When sounds are mixed up or confused, does this cause you to lose concentration on what you were doing or thinking?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

24. You are in a place where sounds seem mixed up and confused. You are by yourself. Do you feel a need to leave that place quickly to go to a place where you will feel more comfortable?

1) Almost Always, 2)Often, 3)Sometimes, 4)Almost never

25. Does wearing your hearing aid(s) increase any feelings of confusion you may experience?

1) Almost Always, 2) Often, 3) Sometimes, 4) Almost never

APPENDIX F

PRE-EXPERIMENT SUBJECT CHARACTERISTICS

Table 4 - Pre-Experiment Subject Characteristics

	Gender		Age Range	Average Age	Average Duration of Hearing Loss	Duration of Hearing Loss Range	Impaired Ear	
	Male	Female					Right	Left
Unilateral Hearing Loss Group (N=20)	9 (45%)	11 (55%)	25–78 years	49.65 years	13.68 years	1-53 years	12 (60%)	8 (40%)
Bilateral Hearing Loss Group (N=10)	6 (60%)	4 (40%)	23-73 years	48 years	15.33 years	5-20 years	N/A	
Control Group (N=20)	4 (20%)	16 (80%)	21-32 years	24.45 years	N/A	N/A	N/A	

APPENDIX G

UNILATERAL HEARING LOSS GROUP – AVERAGE AUDIOGRAM

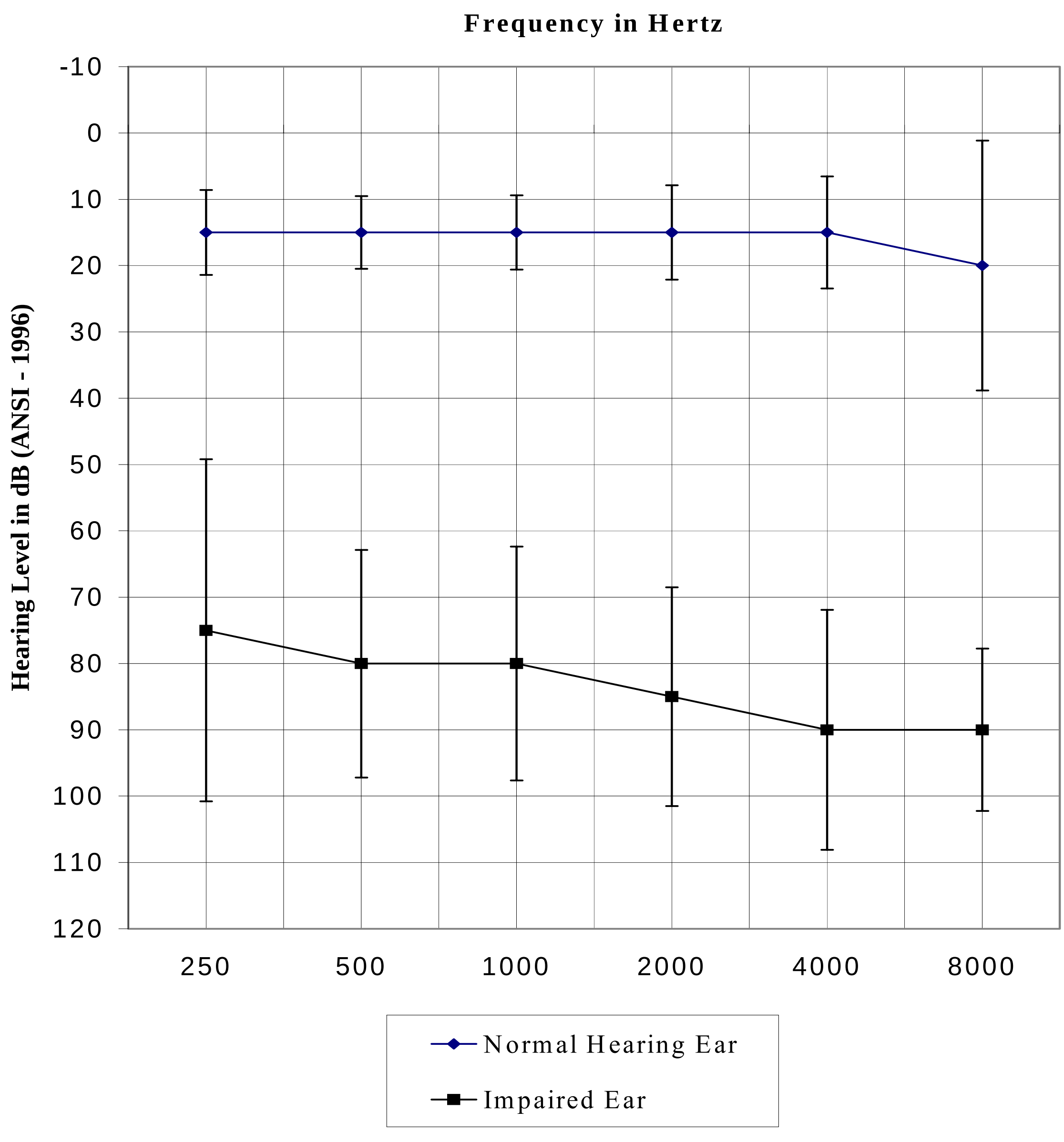

Figure 2- Unilateral Hearing Loss Group - Average Audiogram

APPENDIX H

NORMAL HEARING GROUP – AVERAGE AUDIOGRAM

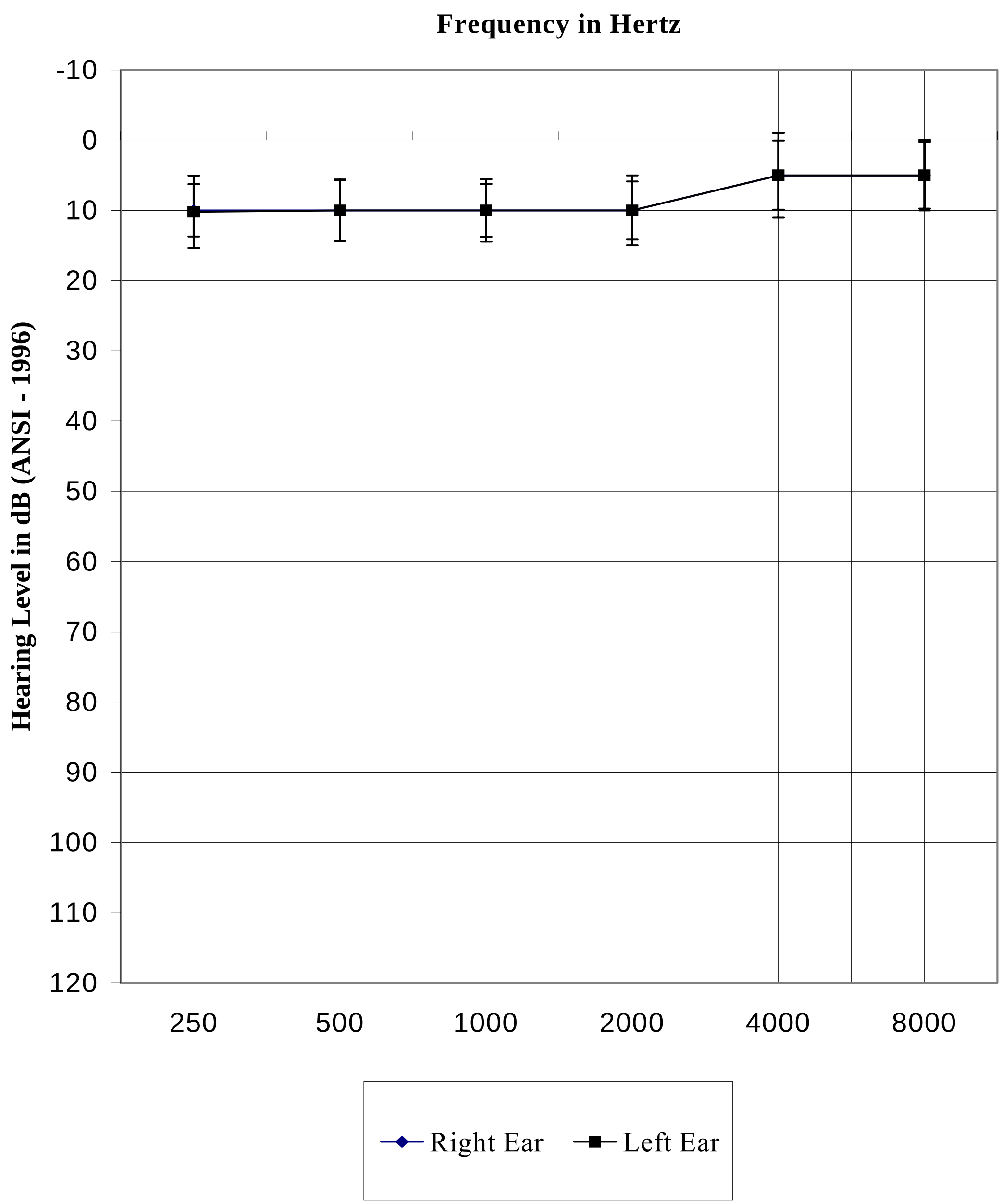

Figure 3 - Normal Hearing Group - Average Audiogram

APPENDIX I

BILATERAL HEARING LOSS GROUP – AVERAGE AUDIOGRAM

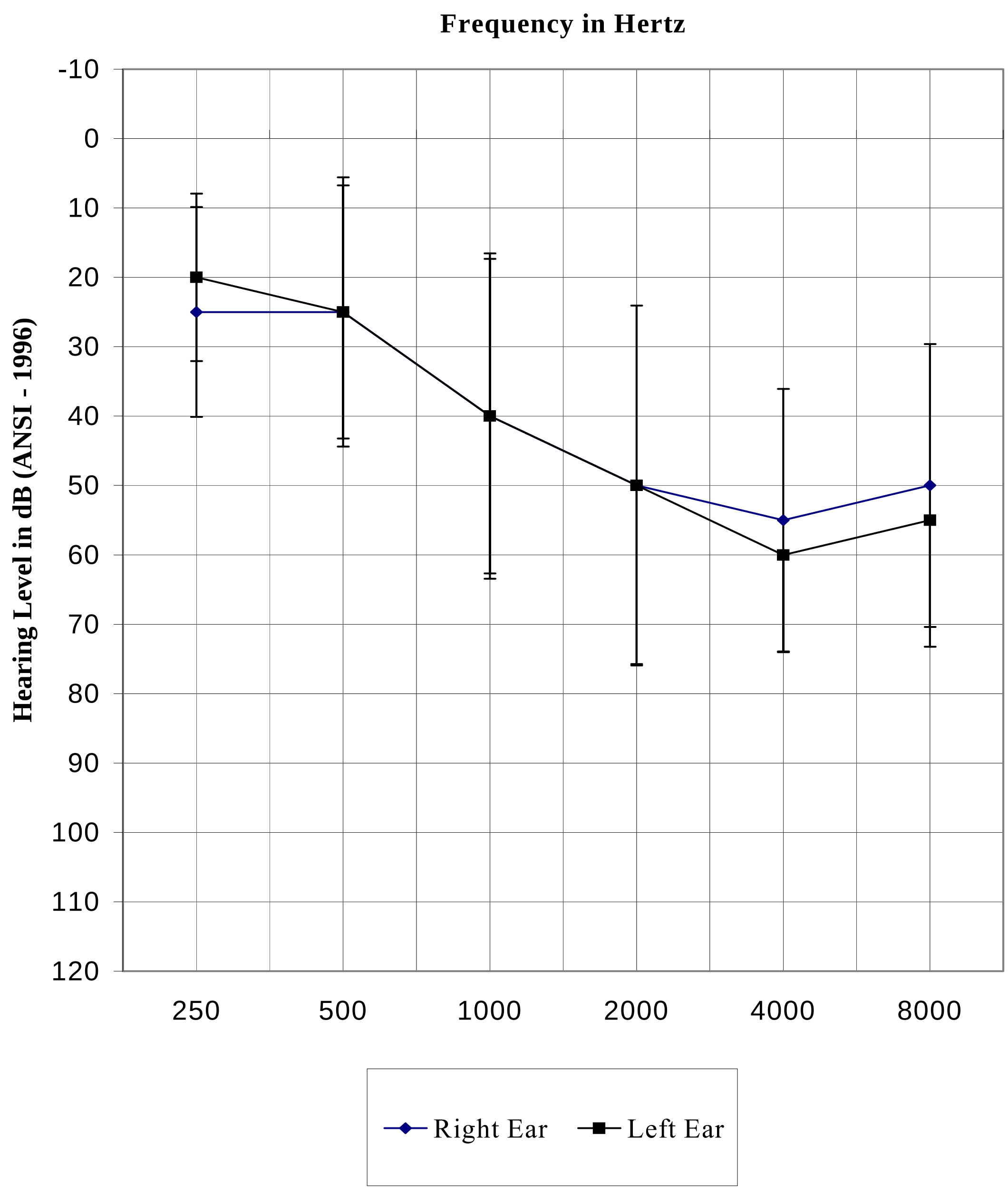

Figure 4 - Bilateral Hearing Loss Group - Average Audiogram

APPENDIX J

VALIDITY ANALYSIS

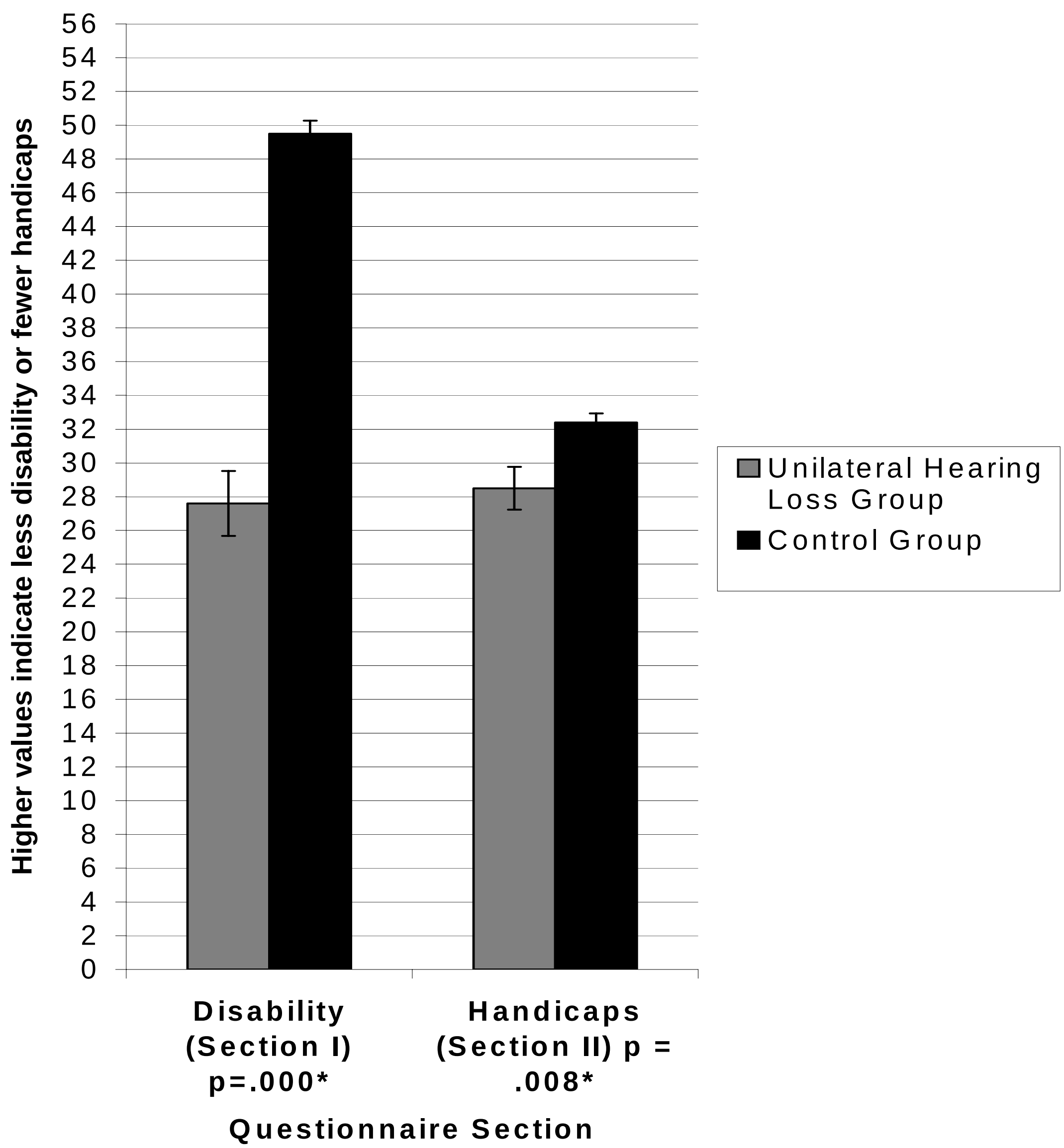

Figure 5 - Validity Analysis

APPENDIX K

MAIN EXPERIMENT SUBJECT CHARACTERISTICS

Table 5 - Main Experiment Subject Characteristics

	Gender		Age Range	Average Age	Average Duration of Hearing Loss	Duration of Hearing Loss Range
	Male	Female				
Unaided Group (N = 57)	38 (67%)	19 (33%)	60-75 years	66.6 years	9.07 years	4 mo. – 50 years
Omni-Directional Only Amplified Subgroup (N=19)	15 (79%)	4 (21%)	60-75 years	65.95 years	8.5 years	6 mo. – 50 years
Directional-Only Amplified Subgroup (N=19)	11 (58%)	8 (42%)	60 – 75 years	66.47 years	8.42 years	2 – 30 years
Toggle Switch Equipped Amplified Subgroup (N=19)	12 (63%)	7 (37%)	60 – 75 years	67.42 years	10.28 years	4 mo. – 30 years

APPENDIX L

UNAIDED GROUP – AVERAGE AUDIOGRAM

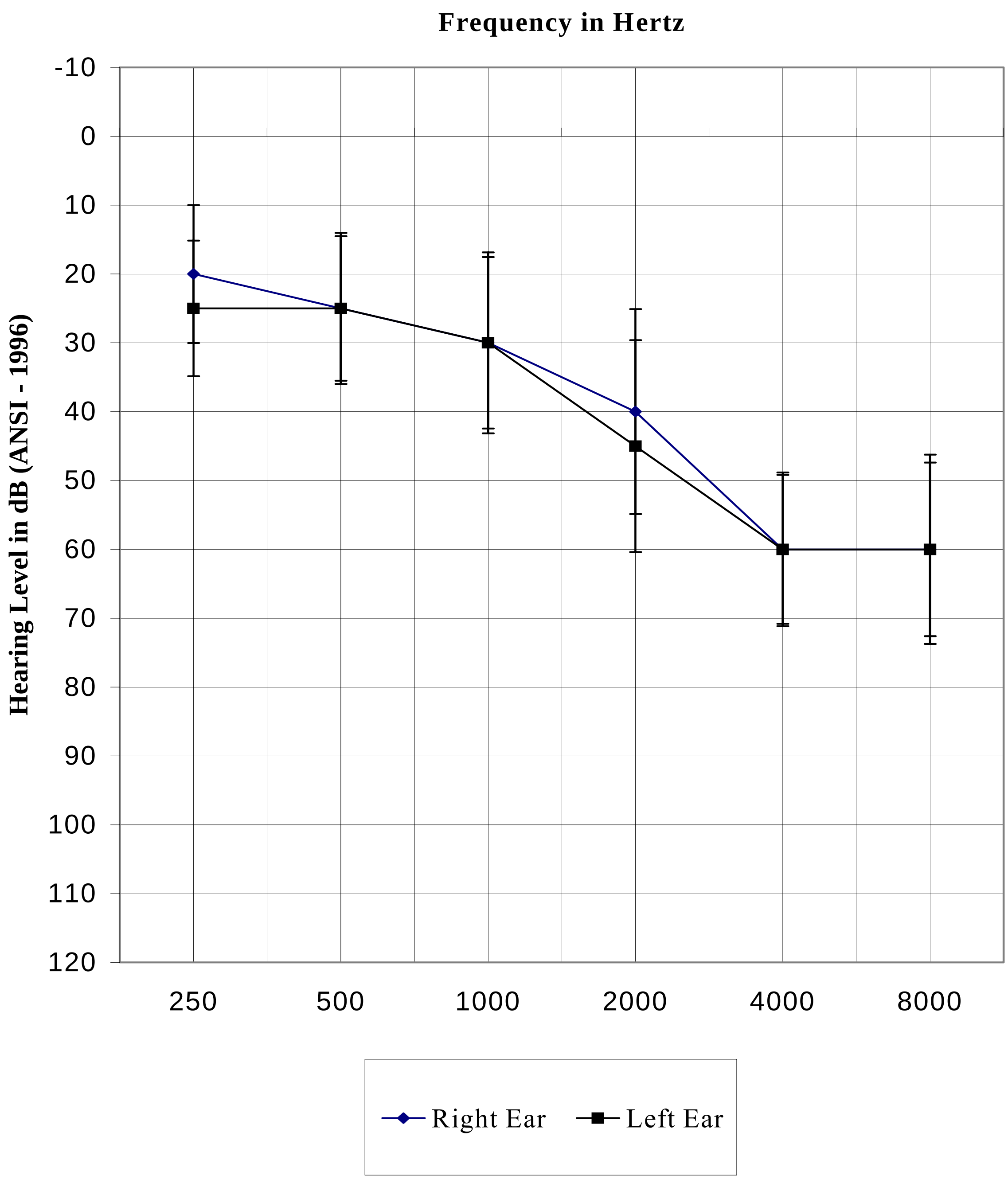

Figure 6 - Unaided Group - Average Audiogram

APPENDIX M

SOCIAL DISENGAGEMENT INDEX

I. Presence of spouse (SPOUSE)

1. Have you ever been married?

(Response codes: 1 = yes, 2 = no [skip Question 2])

2. Are you now married, separated, divorced, or widowed?

(Response codes: 1 = married, 2 = separated, 3 = divorced, 4 = widowed)

If the response to Question 1 = 1 and the response to Question 2 = 1, then code SPOUSE as 1; otherwise, code SPOUSE as 0.

II. Monthly visual contact with three or more relatives and close friends (VISUAL)

III. Yearly nonvisual contact with 10 or more relatives and close friends (NONVIS)

Children:

1. How many children, if any, have you had (including adopted children or children you have raised)? (If none, code Questions 2-4 as 0.)

2. How many are presently living?

3a. How many of your children do you see at least once a week?

3b. Of the others, how many do you see every month?

4a. How many of your children do you talk to on the phone or correspond with weekly?

4b. Of the others, how many do you talk to on the phone or correspond with monthly?

4c. Of the others, how many do you talk to on the phone or correspond with several times a year?

Other relatives:

5. In general, apart from you children, how many other relatives do you have that you feel close to? (People that you feel at ease with, can talk to about private matters, and can call on for help.)

6. How many of these relatives do you see at least once a month?

7. How many of these relatives do you correspond with, either by letter or telephone, a few times a year?

Close friends:

8. In general, how many close friends do you have? (People that you feel at ease with, can talk to about private matters, and can call on for help.)

9. How many of these friends do you see at least once a month?

10. How many of these friends do you exchange letters or telephones calls with a few times a year?

If the response to Questions 3a + 3b + 6 + 9 $\geq$ 3, then code VISUAL as 1; otherwise, code VISUAL as 0.

If the response to Questions 4a + 4b + 4c + 7 + 10 $\geq$ 10, then code NONVIS as 1; otherwise code NONVIS as 0.

IV. Frequent attendance at religious services (CHURCH)

1. About how often do you go to religious meetings or services?

(Response codes: 1 = never or almost never; 2 = once or twice a year; 3 = every few months; 4 = once or twice a month; 5 = once a week; 6 = more than once a week.)

If the response to Question 1 ≥ 4, then code CHURCH as 1; otherwise, code CHURCH as 0.

V. Membership in other groups (GROUPS)

1. Do you participate in any groups, such as a senior center; social or work group; church-connected group; self-help group; or charity, public service, or community group?

(Response codes: 1 = yes [specify]; 2 = no)

If the response to Question 1 = 1, then code GROUPS as 1; otherwise, code GROUPS as 0.

VI. Regular participation in recreations social activities (SOCACT)

Here is a list of things people do in their free time. In the last month, how often have you done each of these things? (Response codes: 0 = never; 1 = sometimes; 2 = often)

1. Active sports or swimming

2. Take walks

3. Work in the garden or yard

4. Do physical exercises

5. Prepare your meals

6. Work at a hobby

7. Go out and do some shopping

8. Go out to a movie, restaurant, or sporting event

9. Read books, magazines, newspapers

10. Watch television

11. Day trips, overnight trips

12. Unpaid community or volunteer work

13. Paid community work

14. Regularly play cards, games, or bingo

15. Any other activities (specify)

Regular participation in recreational social activities:

If the response to Questions $7 + 8 + 11 + 12 + 13 + 14 \geq 6$ (that is, if the mean response = 1), then code SOCACT as 1; otherwise, code SOCACT as 0.

Regular participation in physical activities (not part of the social disengagement index):

If the response to Questions $1 + 2 + 3 + 4 \geq 4$ (that is, if the mean response = 1), then code PHYSACT as 1; otherwise, code PHYSACT as 0.

A composite index of social disengagement was constructed from the six indicators (SPOUSE, VISUAL, NONVIS, CHURCH, GROUPS, and SOCACT). Scoring was as follows: 1=five to six ties, 2 = three to four ties, 3= one to two ties, 4 = no ties. "Tie" refers to the type of social contact. If more than two indicators were missing (questions that were not answered and "don't know" responses were scored as missing), the index was not scored.

APPENDIX N

OMNI-DIRECTIONAL ONLY GROUP – AVERAGE AUDIOGRAM

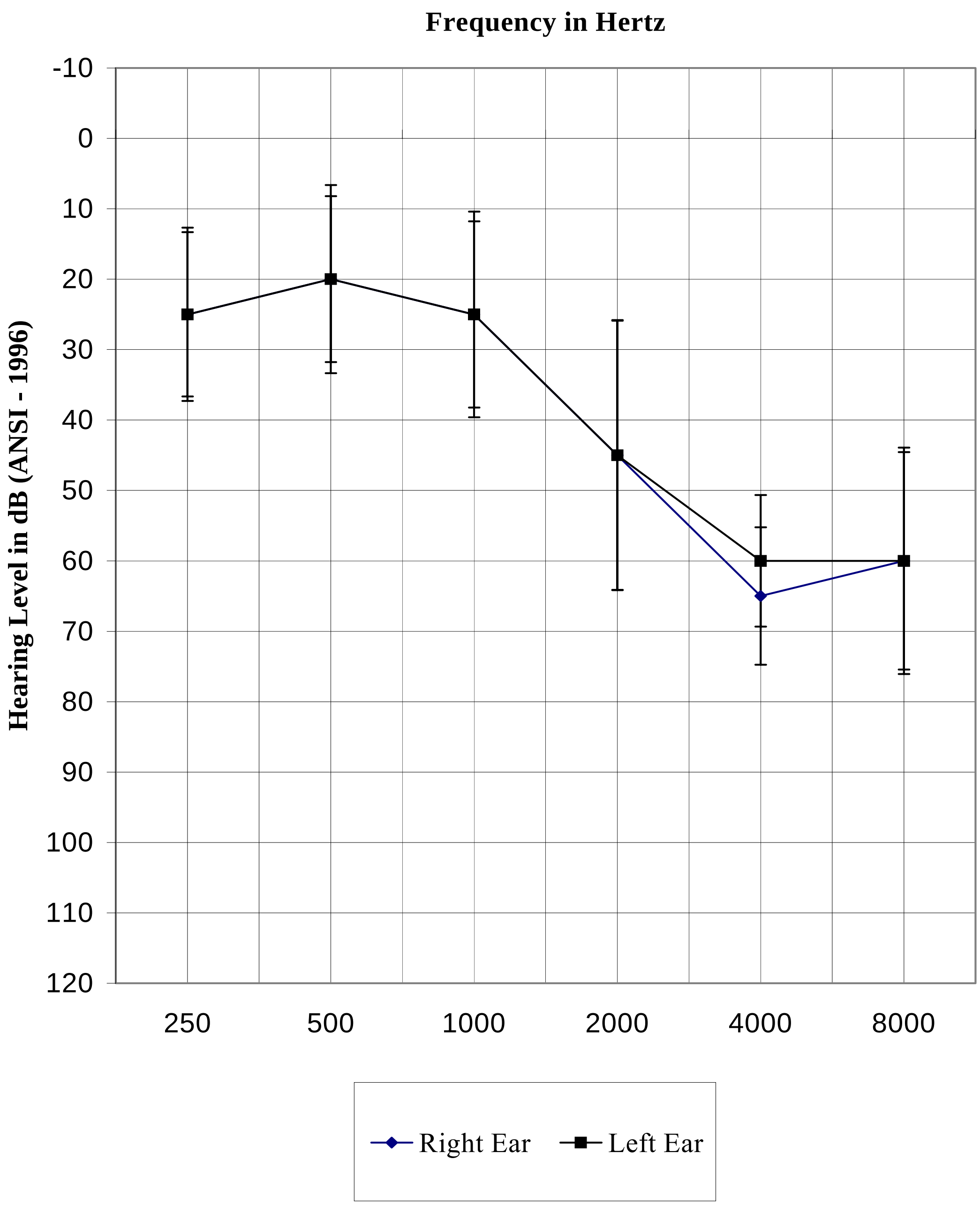

Figure 7 - Omni-directional Only Group - Average Audiogram

APPENDIX O

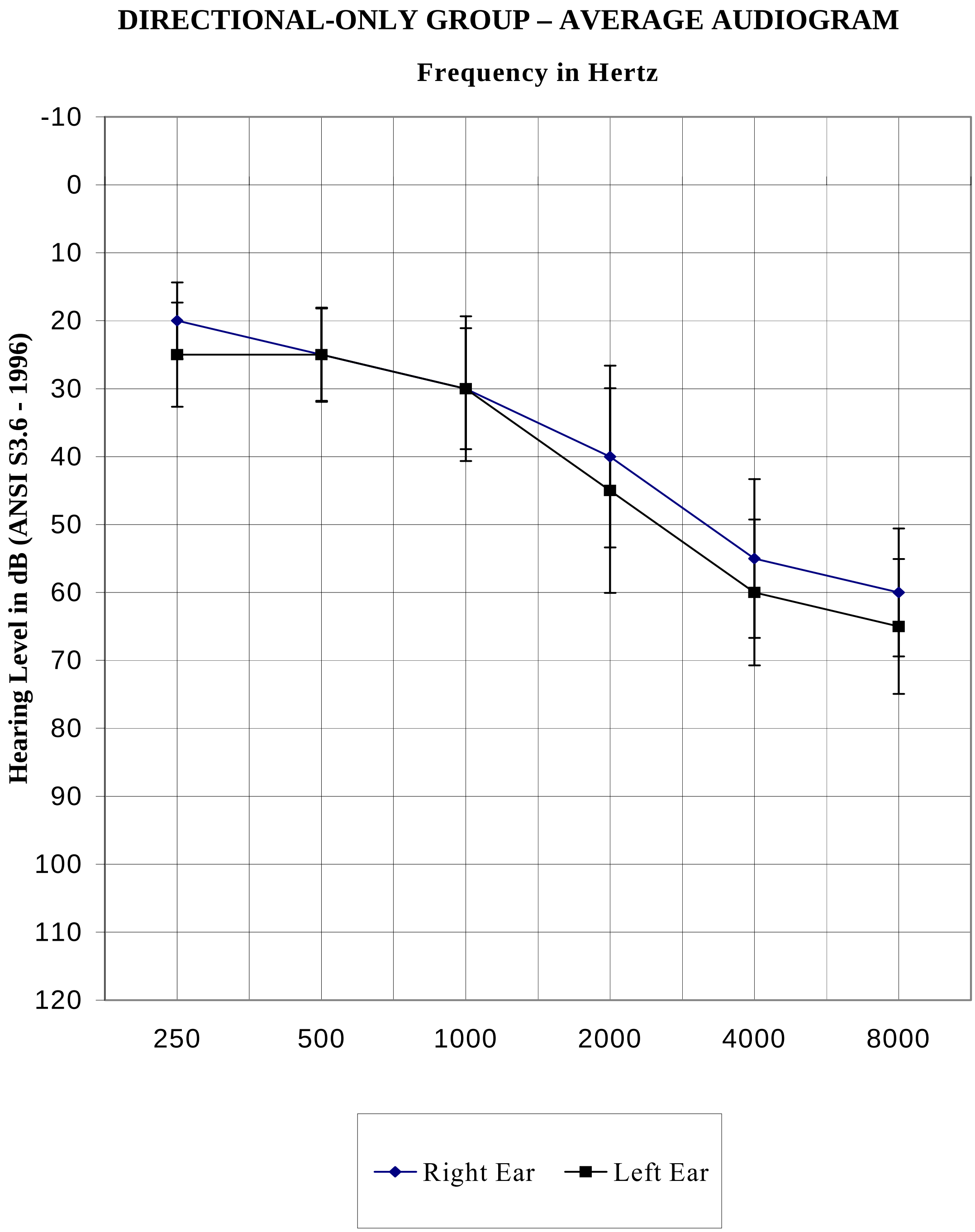

Figure 8 - Directional-only Group - Average Audiogram

APPENDIX P

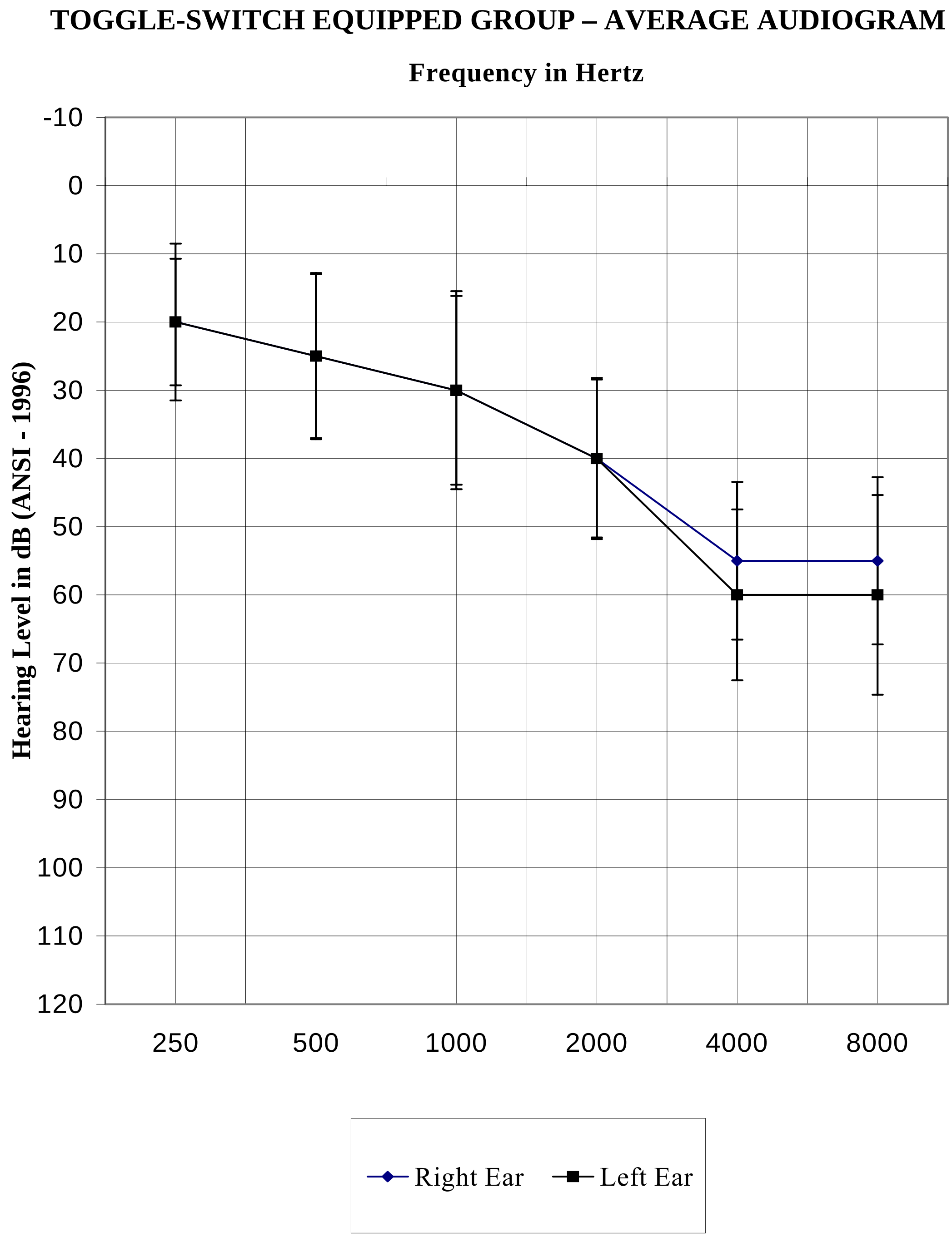

Figure 9 - Toggle-switch Equipped Group - Average Audiogram

APPENDIX Q

CONTOUR TEST OF LOUDNESS PERCEPTION
CATEGORIES OF LOUDNESS

1 – Very Soft

2 – Soft

3 – Comfortable but Slightly Soft

4 – Comfortable

5 – Comfortable but Slightly Loud

6 – Loud but O.K.

7 – Uncomfortably Loud

APPENDIX R

AVERAGE FRONT-TO-ANGLE RATIOS AT HEARING AID FITTING

Table 6 - Average FARs at Hearing Aid Fitting

	Average Front-to-Angle Ratios				
	0˚ - 90˚	0˚ - 135˚	0˚ - 180˚	0˚ -225˚	0˚ - 270˚
Directional-Only Amplified Subgroup	4.62 dB	7.89 dB	10.26 dB	11.32 dB	8.79 dB
Toggle-Switch Equipped Amplified Subgroup	5.48 dB	10.01 dB	10.12 dB	12.35 dB	8.65 dB

APPENDIX S

AVERAGE FRONT-TO-ANGLE RATIOS POST HEARING AID USE

Table 7 - Average FARs Post Hearing Aid Use

	Average Front-to-Angle Ratios				
	0˚ - 90˚	0˚ - 135˚	0˚ - 180˚	0˚ - 225˚	0˚ - 270˚
Directional-Only Amplified Subgroup	4.95 dB	7.25 dB	9.56 dB	10.5 dB	8.46 dB
Toggle-Switch Equipped Amplified Subgroup	5.16 dB	9.26 dB	9.93 dB	11.5 dB	8.56 dB

APPENDIX T

TYPE I VERSUS TYPE II ERROR – DECISION TABLE

Table 8 - Type I - versus Type II - Error Decision Table

Research Question	Possible Outcomes	Outcome Action	Potential Error Type	Erroneous Consequence
Unaided Group (UN) versus Aided Groups Omni-directional only Group (OMNI) Directional-only Group (DIR) Toggle-switch equipped Group (TOG)	UN significantly > OMNI, DIR, or TOG	Recommend amplification	Type I Difference found is not real	None, same recommendation
	OMNI, DIR, or TOG significantly > UN	Recommend amplification Provide precaution counseling	Type I Difference found is not real	Would have provided unnecessary precaution counseling
	UN = OMNI, DIR, or TOG	Recommend amplification	Type II Difference exists but no found	Would not provide necessary precaution counseling. May put subject in unsafe environment

Table 8 (continued)

Research Question	Possible Outcomes	Outcome Action	Potential Error Type	Erroneous Consequence
Directional-only Group (DIR) versus Omni-directional only Group (OMNI)	DIR significantly > OMNI	Recommend Omni-directional amplification	Type I Difference found is not real	Lose the potential benefit of wearing directional microphone technology
	OMNI significantly > DIR	Recommend Directional-only amplification	Type I Difference found is not real	Lose the potential benefit of the toggle-switch option
	DIR = OMNI	Recommend Toggle-switch equipped amplification	Type II Difference exists but not found	May put subject in an unsafe environment when listening in the mode that causes greater localization problems

Table 8 (continued)

Research Question	**Possible Outcomes**	**Outcome Action**	**Potential Error Type**	**Erroneous Consequence**
Directional-only Group (DIR) versus Toggle-switch equipped Group (TOG)	DIR significantly > TOG	Recommend Toggle-switch equipped amplification Provide precaution counseling for when listening in directional mode	Type I Difference found is not real	Would have provided unnecessary precaution counseling
	TOG significantly > DIR	Recommend Directional-only amplification	Type I Difference found is not real	Lose the potential benefit of the toggle-switch option
	DIR = TOG	Recommend Toggle-switch equipped amplification	Type II Difference exists but not found	May put subject in an unsafe environment when listening in the mode that causes greater localization problems

APPENDIX U

GROUP MEAN TOTAL SCORES FOR DISABILITY SECTION QUESTIONS 1-9 AND HANDICAP SECTION QUESTIONS 17& 18 FOR PAIRED SAMPLES T-TESTS COMPARISONS

Table 9 - Group Mean Total Scores for Disability Section Questions 1-9 and Handicap Section Questions 17 and 18 for Paired Samples t-tests Comparisons.

Group	Group Mean Total Scores Disability Section Questions 1-9		Group Mean Total Scores Handicaps Section Questions 17 & 18	
Omni-directional only Group	Unaided	Aided	Unaided	Aided
	3.05	3.06	3.84	3.92
Directional-only Group	Unaided	Aided	Unaided	Aided
	3.04	3.14	3.74	3.87
Toggle-switch equipped Group	Unaided	Aided	Unaided	Aided
	3.20	3.33	3.84	3.82

APPENDIX V

ADJUSTED AIDED GROUP MEAN TOTAL SCORES FOR DISABILITY SECTION QUESTIONS 1-9 AND HANDICAP SECTION QUESTIONS 17 &18 FOR ANCOVA

Table 10 - Adjusted Aided Group Mean Total Scores for Disability Section Questions 1-9 and Handicap Section Questions 17&18 for ANCOVA

Group	Group Mean Total Scores Disability Section Questions 1-9		Group Mean Total Scores Handicap Section Questions 17 & 18	
Omni-directional only Group	Unadjusted Aided	Adjusted Aided	Unadjusted Aided	Adjusted Aided
	3.06	**3.08**	3.92	**3.91**
Directional-only Group	Unadjusted Aided	Adjusted Aided	Unadjusted Aided	Adjusted Aided
	3.14	**3.17**	3.87	**3.90**
Toggle-switch equipped Group	Unadjusted Aided	Adjusted Aided	Unadjusted Aided	Adjusted Aided
	3.33	**3.28**	3.82	**3.80**

APPENDIX W

COMPARISON OF UNAIDED, HEARING IMPAIRED VERSUS NORMALLY HEARING

Table 11 - t-test results for comparison of unaided, hearing impaired versus normally hearing

	Mean total score for Questions 1-9	Standard Deviation	p-value	Mean total score for Questions 17 & 18	Standard Deviation	p-value
Group with normal hearing	3.66	.20	N/A	3.98	.11	N/A
Omni-directional only Group	3.05	.61	p = .001*	3.84	.75	p = .115
Directional -only Group	3.04	.64	p < .0005*	3.74	.34	p = .188
Toggle-switch equipped Group	3.20	.76	p = .018*	3.84	.69	p = .399

APPENDIX X

TRUE EFFECT SIZES

Table 12 - Effect sizes for differences between unaided and aided.

Group	Questions	Effect Size Value	Effect Size Category
Omni-directional only	1-9	.02	Very Small[1]
	17 & 18	.26	Small[1]
Directional-only	1-9	.16	Small[1]
	17 & 18	.16	Small[1]
Toggle-switch Equipped	1-9	.20	Small[1]
	17 & 18	.23	Small[1]

[1] Cohen defines a small effect as d=.2, a medium effect as d=.5, and a large effect as d=.8.

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