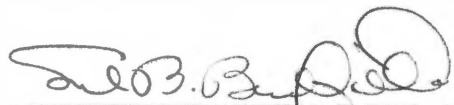


To the Graduate Council:

I am submitting herewith a thesis written by Melinda Carol Freyaldenhoven entitled "Quantification of Directional Hearing Aid Benefit: Comparison of Acceptable Noise Level, Masked Speech Recognition Threshold, Ear Canal Signal-to-Noise Ratio, and Abbreviated Profile of Hearing Aid Benefit." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Audiology.

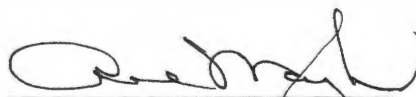


Samuel B. Burchfield, Major Professor

We have read this thesis and  
recommend its acceptance:



Acceptance for the Council:



Vice provost and Dean of  
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**QUANTIFICATION OF DIRECTIONAL HEARING AID  
BENEFIT: COMPARISON OF ACCEPTABLE NOISE  
LEVEL, MASKED SPEECH RECOGNITION THRESHOLD,  
EAR CANAL SIGNAL-TO-NOISE RATIO, AND  
ABBREVIATED PROFILE OF HEARING AID BENEFIT**

**A Thesis**

**Presented for the Master of Arts Degree  
at the University of Tennessee, Knoxville**

**Melinda Carol Freyaldenhoven**

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## Abstract

Directional benefit in hearing aids was quantified physically with ear canal signal-to-noise ratio (SNR), perceptually with masked speech recognition threshold (SRT) testing, and subjectively with formal questionnaires. An additional, behavioral method for quantifying the beneficial effects of directional microphones in hearing aids was evaluated in this investigation. This method is the acceptable noise level (ANL), which was developed by Nabelek et al. (1991).

ANL was established by selecting the maximum acceptable background noise (multi-talker speech babble) while listening to speech (male running speech) presented at the most comfortable listening level (MCL). The speech and background noise were presented at  $0^{\circ}$  and  $180^{\circ}$  azimuth, respectively. Monaural and binaural measurements were obtained. The ANL was calculated by subtracting the maximum background noise level (BNL) from the MCL for speech ( $ANL = MCL - BNL$ ).

Results of this investigation showed that the mean directional benefit assessed with ANL (mean improvement = 3.53 dB), masked SRT (mean improvement = 3.23 dB), and ear canal SNR (mean improvement = 3.04 dB) are not significantly different. This suggests that directional benefit can be assessed using either of the assessment paradigms (ANL, masked SRT, and ear canal SNR). Abbreviated Profile of Hearing Aid Benefit (APHAB) results also showed a significant percentage increase in directional benefit for the background noise subtest. Directional hearing aid benefit was not different for measures of benefit between hearing aids with analog and digital circuits or hearing aids with different directional polar plots.

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## CHAPTER I

### Introduction and Rationale

Directional microphones are electroacoustical transducers designed to be most responsive to acoustical signals arriving from a specific direction which is usually  $0^\circ$  azimuth (Stach, 1997). In hearing aids, directional microphones maintain sensitivity to signals arriving from the front while suppressing signals arriving from the sides and back (Dillion, 2001). At this time, there is no standard method for evaluating the performance of directional hearing aids; however, literature reports have shown beneficial effects for these devices physically, perceptually, and subjectively.

The net effect of hearing aid directional benefit is improvement in physical signal-to-noise ratio (SNR) between speech and background noise. Literature reports have documented this physical beneficial effect in the soundfield (Kuhnel, Margolf-Hackl, and Kiessling, 2001; Norwood and Thelin, 2001; Valente, Fabry, and Potts, 1995; and Wouters, Litiere, and van Wieringen, 1999) and in the ear canal (called ear canal SNR) (Dhar, Calandruccio, Humes, Barlow, and Hipkind, 2002, and Ricketts, 2000).

Improvements in SNR have also been shown to improve word recognition scores (WRS) and speech recognition thresholds (SRT) in background noise (WRS: Gravel, Fausel, Liskow, and Chobot, 1999; Kuk, Kollofski, Brown, Melum, and Rosenthal, 1999; Lentz, 1972; Nielsen, 1973; and Ricketts and Mueller, 2000; and SRT: Agnew and Block, 1997; Frank and Gooden, 1972; and Kuhnel et al., 2001). The typical paradigm for these investigations has been to deliver speech stimuli from  $0^\circ$  azimuth and background noise from other locations including  $90^\circ$  and/or  $270^\circ$  azimuth (Nielsen, 1973, and Wouters et al., 1999) or  $180^\circ$  azimuth (Kuhnel et al., 2001, and Kuk et al., 1999).

Because directional microphones attenuate signals arriving from the sides and back, the WRS and SRT improve in comparison to the omni-directional condition.

Informal and formal subjective quality ratings have also been employed to quantify the beneficial effects of hearing aid directional benefit. The Abbreviated Profile of Hearing Aid Benefit (APHAB) developed by Cox and Alexander (1995) has been used to show this beneficial effect with directional hearing aids (Kuk, 1996; Nielsen, 1973; Preves, Sammeth, and Wynne, 1999, and Schuchman, Valente, Beck, and Potts, 1999).

In 1991, Nabelek, Tucker, and Letowski developed a procedure to quantify the amount of background noise individuals are willing to accept while listening to speech. The first step in this procedure is establishment of the most comfortable listening level (MCL) for speech. Next, background noise is added and adjusted to the maximum acceptable background noise level (BNL). The acceptable noise level (ANL) is then determined by subtracting the BNL from the MCL ( $ANL = MCL - BNL$ ), all in decibels (dB).

Independent investigations about the relationship between ANL scores and hearing aid use (Crowley, 1994; Lytle, 1994; and Nabelek et al, 1991) have shown that successful hearing aid users accept more background noise than unsuccessful users. In these investigations both the speech and the background noise were presented from  $0^0$  azimuth. In this study, however, speech and background were presented from  $0^0$  and  $180^0$ , respectively. Pilot investigations in the present investigation, using normal and pathological subjects, revealed that this experimental paradigm (speech at  $0^0$  azimuth and background noise at  $180^0$  azimuth) does not significantly alter ANL scores when quantifying directional benefit (see Appendix A).

Pilot investigations also demonstrated that it is possible to quantify hearing aid directional microphone benefit with the ANL procedure. Pilot data, with speech at 0° azimuth and background noise at 180° azimuth, indicated that more background noise was accepted for the directional listening condition. As a result of this finding, the present investigation was conceived to independently evaluate the relative merits of each procedure (ANL, masked SRT, ear canal SNR, and APHAB) in the quantification of hearing aid directional benefit. The benefit results were then compared to determine which measure was the most useful tool in quantifying microphone directional benefit in hearing aids. A large subject cohort (N=40) was recruited to include both analog and digital directional instruments with a variety of polar plots. In order to fully explore the directional benefit with each procedure, the subjects were tested both monaurally and binaurally.

## CHAPTER II

### Review of Literature

#### Directional Microphones

The most frequent complaint of hearing aid users is difficulty understanding speech in background noise; therefore, a primary rehabilitation goal is to improve SNR between speech and background noise (Kochkin, 1993). Directional microphones in hearing aids have shown promise in achieving this rehabilitation goal (Buerkli-Halevy, 1986; Hillman, 1981; and Nielsen, 1973).

In the 1970's, some hearing aid manufacturers experienced difficulty developing directional microphones in hearing aids. This led to questions about the effectiveness of directional microphones (Valente, 1996) and a twenty-year period of disinterest in directional hearing aids. In the 1990's, a number of studies rekindled interest in directional microphones in hearing aids by documenting improved speech perception in noise for directional listening conditions (Kuhnel et al., 2001; Kuk et al., 1999; Preves et al., 1999; Ricketts and Dhar, 1999; Ricketts and Mueller, 2000; and Walden, Surr, Cord, Edwards, and Olson, 2000). Other investigations have shown improvement in the SNR ranging from 3.4-13.7 dB for the directional listening condition (Valente, Schuchman, Potts, and Beck, 2000; and Wouters et al., 1999).

Nielsen (1973) evaluated speech perception using hearing aids with omni-directional and directional microphones. Twenty-two experienced binaurally fitted hearing aid users ranging in age from 17 to 68 years were investigated. The subjects were binaurally fitted with Oticon (type 568) behind-the-ear (BTE) hearing aids with omni-directional and directional capabilities. The speech stimuli was presented at 0°

azimuth while the competing stimulus was presented from  $90^0$ ,  $180^0$ , and  $270^0$  azimuth. The speech stimulus was maintained at 55 dB SPL while the competing stimulus (cafeteria noise) varied to create four different SNRs (+5, +10, +15, and +20 dB). The investigators found a significant directional microphone advantage (increase in discrimination scores of 17.2% and 18.2% with a SNR of +5 and +10 dB, respectively) over the omni-directional condition. However, with a SNR of +15 and +20 dB, the increase in discrimination scores was not significant (4.1% and 3.2% respectively). The difference in the increase in discrimination scores at +5 and +10 dB SNR versus the +15 and +20 dB SNR might have been due to the ceiling effect.

Nielsen (1973) also obtained subjective performance ratings for daily listening situations with omni-directional and directional conditions. The subjective evaluation showed a significant preference in favor of the directional microphone condition in inferior listening situations (i.e. background noise); however, the subjects found it difficult to hear important environmental noises, such as the doorbell and telephone, arriving from behind. This investigation suggests the hearing aid user should direct themselves towards the speech and away from the background noise to best control the acoustic environment, thus increasing the SNR but still being able to hear environmental stimuli.

A more recent study performed by Valente et al. (1995) compared directional and omni-directional microphone conditions based on increase in SNR using the Hearing in Noise Test (HINT) (Soli and Nilsson, 1994). Twenty-five experienced, adult hearing aid users were evaluated at the Hearing Laboratory at Washington University School of Medicine in St. Louis, Missouri. Another twenty-five subjects were evaluated at the

Hearing Laboratory at the Mayo Clinic in Rochester, Minnesota. The subjects were binaurally fitted with Phonak Audio-Zoom BTE hearing aids and evaluated based on four experimental conditions: 1) basic National Acoustical Laboratory-Revised (NAL-R) frequency response with omni-directional microphone, 2) basic NAL-R frequency response with directional microphone, 3) “party” frequency response with omni-directional microphone, and 4) “party” frequency response with directional microphone. The party frequency response was designed to provide comfort to the hearing aid user in unfavorable listening situations. The speech stimulus (20 HINT sentences) was presented at  $0^{\circ}$  azimuth, and the noise, which was temporally and spectrally matched to the sentences, was presented at  $180^{\circ}$  azimuth. The level of the speech was increased or decreased in 2 dB steps. When 50 percent sentence recognition was achieved, the SNR was recorded. These procedures were administered in both the omni-directional and directional microphone conditions. Results of this investigation revealed an average improvement in SNR of 7.9 dB for the directional (“party”) versus the omni-directional (basic) conditions (Valente et al., 1995).

Gravel et al. (1999) examined speech recognition abilities for words and sentences in background noise using dual-microphone technology in 20 children with bilateral cochlear hearing loss. The children were aided with binaural programmable hearing aids (Phonak PiCS) and were tested in omni-directional and directional (“Audio-Zoom”) conditions. The speech stimuli, words and sentences from the Pediatric Speech Intelligibility test (Jerger and Jerger, 1984), were presented through a loudspeaker at a fixed level of 50 dB HL at  $0^{\circ}$  azimuth while the competing stimulus, multi-talker babble noise, was presented at  $180^{\circ}$  azimuth. Initially, the level of the competing stimulus was

increased in 6 dB steps until the child missed two out of three speech items. The intensity of the competing stimulus was then increased and decreased in 2 dB steps using the same two-out-of-three decision rule. SRT was then estimated for two types of stimuli (closed-set words and sentences). The investigators found that in the directional condition, the hearing aids provided a significant advantage over omni-directional condition while listening in background noise for both words and sentences. The benefit using words and sentences in the directional condition was 4.7 dB.

Kuk (1996) compared subjective performance ratings of 100 satisfied Phonak 232 X-AZ BTE hearing aid wearers when allowed to switch between omni-directional and directional listening conditions. Kuk found that listeners preferred the omni-directional condition in quiet listening situations such as watching television, listening to the radio, participating in a small group discussion, or listening to non-speech sounds such as the music or environmental sounds. In more noisy situations such as restaurants or large group settings, the listeners preferred their hearing aids in the directional condition. This suggests that individuals need to be able to select either omni-directional or directional microphone operations depending on their listening situation.

### Circuitry of Hearing Aids

Hearing aids can be classified according to whether they are analog, analog with digital controls for programming purposes, or digital (Dillion, 2001). Analog hearing aids allow for the direct representation of different voltages through different strengths or pressures on the microphone of the hearing aid (Staab and Lybarger, 1994). These pressures are represented in the amplifier in a proportional voltage relationship with the

input pressures. Adjustments for these circuits, made mechanically, alter the characteristics of one of the signal processing blocks (ex. low-frequency emphasis, high-frequency emphasis, audiometric configuration, saturated sound pressure levels, etc.) by adjusting the value of small variable resistors, called potentiometers (Dillion, 2001).

Digitally programmable analog hearing aids contain a conventional analog sound path but are controlled by an external digital source. These hearing aids usually contain an electronically erasable programmable read only memory, which replaces the conventional trimmer potentiometer. The programmable memory controls the characteristics of each of the analog signal processing blocks, which allows for increased flexibility in how the signal path is altered (Staab and Lybarger, 1994).

Digital hearing aids contain an analog-to-digital converter, which changes analog signals into digital signals. These signals are then processed before being converted back into an analog signal, which is applied to the receiver and then applied to the ear. Digital hearing aids are able to perform more complex signal processing and make decisions about how to process sound based on the overall acoustic environment. Because of the advances in technology, extra features (i.e. feedback managers, etc.) may be added to these devices with little or no effect on physical size or power consumption (Dillion, 2001).

### Polar Plots of Directional Microphones

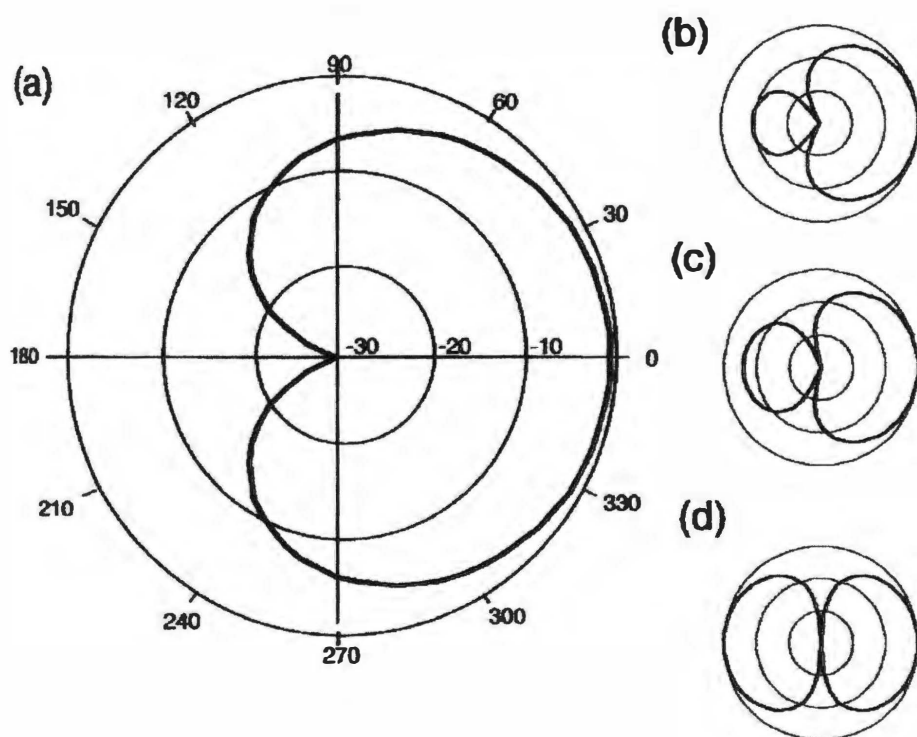
Polar plots describe the directional sensitivity of microphones. Omni-directional microphones, if measured in a free field, are equally sensitive to sounds from all directions, thus having a circular polar sensitivity pattern. Directional microphones may

have 5 different polar sensitivity plots including cardioid, super-cardioid, hyper-cardioid, bi-directional, or adaptive polar plots. Cardioid polar plots are heart-shaped with maximum attenuation of sound at  $180^{\circ}$  azimuth. As the shape of polar plots moves from cardioid to super-cardioid to hyper-cardioid, the sensitivity to sounds arriving from the back increases while the sensitivity to sounds arriving from the sides diminishes. In the bi-directional pattern, the sensitivity to the front and rear are equal, but the microphone is minimally affected by sounds arriving from the sides. Because of its configuration, the bi-directional pattern has also been referred to as a figure-8. Adaptive patterns alter the polar plot based on the acoustic environment. For example, if the microphone “thinks” it is detecting speech in the front and noise in the rear, the polar plot may change to that of a cardioid pattern; however, if the microphone “thinks” it is detecting speech arriving from both the front and back, the polar plot may change to that of a bi-directional pattern (See Figure 1 for a pictorial representation of the above polar plots) (Dillion, 2001).

### Acceptable Noise Level

Nabelek et al. (1991) introduced a procedure for quantifying the amount of background noise that individuals are willing to accept while listening to speech. In this procedure, running speech is adjusted to the most comfortable level (MCL). Next, background noise is adjusted to the maximum intensity, which would be accepted for long periods of time while listening to and following the speech (Nabelek et al., 1991). The acceptable noise level (ANL), expressed in decibels (dB), is the intensity level of the speech at MCL minus the intensity the background noise level (BNL).

Figure 1: Directional sensitivity of a microphone with (a) a cardioid polar plot, (b) supercardioid polar plot, (c) a hypercardioid response, and (d) a bi-directional polar plot, all measured in unobstructed sound field. (Dillion, 2001)



ANL was investigated in 5 groups of 15 subjects each by Nabelek et al. (1991). The groups consisted in the following: (1) young people with normal hearing sensitivity; (2) elderly people with normal hearing sensitivity; (3) elderly people with hearing loss that used their personal hearing aids on a full-time basis (i.e. individuals who wore their hearing aids when they needed them); (4) elderly people with hearing loss that used their personal hearing aids on a part-time basis (i.e. individuals that wear their hearing aids only occasionally); and (5) elderly people with hearing loss who were considered to be non-users (i.e. individuals that rejected their hearing aids). The groups with hearing loss listened, with earphones, to speech and background noise that was filtered to approximate listening with hearing aids. Five different types of background noise including speech spectrum noise, speech babble noise, music, traffic noise, and a pneumatic drill noise were investigated. The mean ANL values (referred to as tolerated speech-to-noise ratios) for the two groups with normal hearing were 15.7 dB (young) and 11.7 dB (elderly) and for the hearing-impaired groups were 7.5 dB (full-time users), 14.0 dB (occasional users), and 14.5 dB (non-users). For all groups and noises, there were large ranges of ANL scores from -2 to 37 dB. The full-time hearing aid users accepted significantly more background noise than listeners in the other groups. The mean ANL values for the remaining groups, young and elderly with normal hearing and hearing-impaired who either rejected their hearing aids or used them only occasionally were not significantly different. It therefore appears that the ANL is related to hearing aid use but not to age or hearing status.

Lytle (1994) compared ANL scores between 2 matched groups of 10 individuals with hearing impairment. The groups were comprised of individuals who were full-time

hearing aid wearers and non-users, respectively. The groups were matched for age, hearing sensitivity, and speech perception ability. Comparisons were made while the subjects listened with and without one of their personal linear analog hearing aids. The full-time hearing aid wearers accepted significantly higher levels of background noise than the non-users both with and without amplification. These results agree with the Nabelek et al. (1991) results suggesting that the acceptance of background noise while listening to speech is related to hearing aid use.

Crowley (1994) included the acceptance of background noise in a battery of test used to predict hearing aid use, satisfaction, and performance. Forty-six adult subjects with acquired sensorineural hearing loss were investigated. Results of this study revealed that hearing aid use was predicted by many factors, including acceptable signal-to-noise levels (called tolerated noise levels in this study) for speech spectrum and speech babble noise.

Fisher, Burchfield, and Nabelek (1999) investigated the reliability of ANL scores and the relationship between subjective preference for background noise in everyday life situations (such as background music) in 12 young, female individuals with normal hearing sensitivity. ANL scores were determined to be reliable both within a session and between sessions for both speech spectrum background noise ( $r = 0.86$ ,  $p < 0.001$ ) and speech babble background noise ( $r = 0.84$ ,  $p < 0.001$ ). Subjects in this study reported their preference for background noise in a questionnaire format. A weak relationship was found between an individual's personal preference for background noise and their ANL for both speech spectrum noise ( $r = 0.19$ ,  $p < 0.05$ ) and speech babble ( $r = 0.14$ ,  $p < 0.05$ ), suggesting that personal preference for background noise is not a good indicator of

the actual amount of background noise an individual will accept while listening to speech.

Freyaldenhoven and Fisher-Smiley (2001) investigated normative ANL scores and reliability in two groups of children. The groups contained 16 eight-year olds and 16 twelve year olds with normal hearing sensitivity. The average ANL scores for the eight (9.9 dB) and the twelve (12.1 dB) year olds when speech spectrum noise was the competing stimuli were not significantly different. The range for the eight and twelve year olds was -2 to 23 dB and -3 to 22 dB, respectively. The average ANL scores for the eight (9.1 dB) and twelve (10.2 dB) year olds when speech babble was the stimulus were also not significantly different. The range for the eight and twelve year olds was -6 to 28 dB and -3 to 24 dB, respectively. ANL scores were determined to be reliable within a session for speech spectrum background noise in both the eight ( $r = 0.86$ ,  $p < 0.001$ ) and twelve year old groups ( $r = 0.96$ ,  $p < 0.001$ ) and for speech babble background noise for the eight ( $r = 0.82$ ,  $p < 0.001$ ) and twelve year children ( $r = 0.96$ ,  $p < 0.001$ ).

For comparison purposes, the data collected on the eight and twelve year old children was combined. This data was then compared with the data for the young, normal hearing subjects (from both the Nabelek et al., 1991 and Fisher et al., 1999 studies) and to the data for elderly, normal hearing subjects (from Nabelek et al., 1991). When speech spectrum was the competing stimuli, the average ANL score was 11.0 dB, and the range was -3 to 23 dB for 32 children (Freyaldenhoven et al., 2001). In comparison, the average ANL score for the young, normal hearing group was 14.1 dB, and the range was 5 to 28 dB for 27 young individuals (15 from Nabelek et al., 1991 & 12 from Fisher et al., 1999). The average ANL score for the elderly, normal hearing

group was 12.7 dB, and the range was 2 to 23 dB for 15 elderly individuals (Nabelek et al., 1991). Results of independent t-tests revealed that the means of the children and the young, normal hearing groups were statistically different ( $t = -2.12$ ,  $p = 0.038$ ), but the means were not different between the children and the elderly group ( $t = -0.74$ ,  $p = 0.466$ ).

With speech babble noise as the competing stimuli, the average the ANL score for the children was 9.7 dB, and the range was -6 to 28 dB. Again, in comparison, the average ANL score for the young, normal hearing group was 14.1 dB, and the range was 5 to 28 dB for 27 young individuals (15 from Nabelek et al., 1991 and 12 from Fisher et al., 1999). The average ANL score for the elderly, normal hearing group was 11.7 dB, and the range was 0 to 27 dB. Results of the independent t-tests again found the means of the children to be statistically different from the means of young adults ( $t = -2.79$ ,  $p = 0.007$ ) but not different from the elderly adults ( $t = -1.00$ ,  $p = 0.322$ ).

Franklin, Burchfield, and Nabelek (2001) compared ANL scores with uncomfortable listening levels (UCL) in 33 young individuals with normal hearing sensitivity. Subjects were evaluated three times during two sessions about 3-5 days apart. The UCL was defined as the intensity level at which sound was judged to be uncomfortably loud. Results from this study revealed that the ANL values were independent of the UCL measurement ( $r = -0.03$ ,  $p = 0.89$ ). A relationship has yet to be established between ANL and any other clinical, audiometric measures.

Rogers, Harkrider, Burchfield, and Nabelek (2002) investigated gender as a possible contributing factor in the subject variability in ANL scores. Fifty (25 male and 25 female) normal hearing adults between 19 and 25 years of age were asked to perform the ANL tasks developed by Nabelek et al. (1991). The primary stimulus (Audiotech

recording of male running speech) was presented at  $0^{\circ}$  azimuth, and the background noise (multi-talker speech babble) was presented at  $180^{\circ}$  azimuth. Subjects were tested in one thirty-minute session, in which they listened binaurally in an audiometric sound booth. During the session the subject reported one judgment of their MCL and three judgments of their maximum acceptable BNL while listening to speech at MCL. The ANL was calculated by subtracting the average of the three judgments of the BNL from the MCL judgment. Results of this study showed no significant difference in ANL scores based on gender. There was, however, a statistical significance between the gender of the listener and the MCL reported, with males having higher MCLs.

### Speech Recognition Testing

In 1973, Tillman and Olsen described a descending procedure (Hudgins, Hawkins, Karlin, and Stevens, 1947) for establishing the speech recognition threshold (SRT) using spondee words. The first step in this procedure is familiarization by reading the spondee words. The listener is then instructed through written or verbal instructions to repeat the words that are heard through a loudspeaker. The listener is informed that the words will become very soft and encouraged to guess. The procedure is usually performed using recorded spondaic words. The following are a list of steps used during administration of the Tillman and Olsen (1973) procedure:

- 1) A single spondee word is presented at approximately 30 dB sensation level.
- 2) If the spondee word is repeated correctly, the signal is attenuated by 10 dB, and another spondee is presented.

- 3) When two consecutive incorrect responses occur, the intensity is increased by 10 dB. This is called the “starting level.”
- 4) Two spondaic words are presented at each level, decreasing the intensity in 2 dB steps.
  - a. Five out of the first six words must be repeated correctly, or the starting level must be re-established 4 to 6 dB above the original starting level.
- 5) This process continues until at least 5 out of the last six words are missed.
- 6) Threshold is then calculated in the following manner:
  - a. The starting level is recorded.
  - b. The number of correct responses is subtracted from the starting level.
  - c. A correction factor, which is one half the attenuation rate (or 1 dB), is added to the number obtained.

Tillman and Olsen (1973) reported that the result obtained from the above procedure approximates the 50% criterion typically used to represent threshold on an articulation curve. They also reported that this procedure was less time consuming and reduced variability in determining SRT because there was an established definition of threshold.

### Abbreviated Profile of Hearing Aid Benefit

The Abbreviated Profile of Hearing Aid Benefit (APHAB) (Cox & Alexander, 1995) was developed to assess auditory functioning disabilities in daily life situations. This 24 item questionnaire obtained information in four areas: (1) Ease of Communication, (2) Reverberation, (3) Background Noise, and (4) Aversiveness of

Sounds. The Ease of Communication scale determined the effort one must exert to communicate in relatively easy listening situations. Speech understanding in moderately reverberate environments is addressed in the Reverberation scale. The Background Noise scale deals with speech understanding when competing stimuli are present. Finally, the Aversiveness of Sounds scale determined negative reactions to loud environmental sounds. Each question is judged by the hearing aid wearer on the following seven point scale: always (99%), almost always (87%), generally (75%), half-the-time (50%), occasionally (25%), seldom (12%), and never (1%). Performance is determined based on both aided and unaided listening conditions.

## CHAPTER III

### Methods and Procedures

#### Subjects

Forty adult patients from the University of Tennessee Hearing and Speech Clinic served as experimental subjects. These subjects were selected for inclusion on the basis of (1) being fitted binaurally with hearing aids containing both omni-directional and directional conditions and (2) having worn their hearing aids for at least three months. Subjects used for this study had hearing aids with the following circuits and polar plots: analog (N=15), digital (N=25), hypercardiod (N=22), supercardiod (N=2), bi-directional (N=1), and adaptive (N=15).

Subjects were evaluated during a single session lasting approximately 1.5 hours. The hearing aids were fitted and adjusted by the Hearing and Speech Center audiologists. Audiometric results including pure tone threshold sensitivity were obtained from each subject's clinic file. Each subject signed an informed consent form (see Appendix B) before participating in this study. Following the study, each subject was paid \$20.00 for participation.

#### Procedure

##### Acceptable Noise Level

ANL scores were determined using the procedure developed by Nabelek et al. (1991). Subjects were given two hand-held buttons with which to first adjust the intensity of the speech (Arizona Travelogue, Cosmos Inc.) to their MCL. Then the competing stimulus (multi-talker speech babble) was added, and the subject adjusted the

intensity of the background noise to their maximum acceptable BNL while listening to and following the speech. The buttons were connected to an indicator box that signaled the examiner to manipulate the intensity level of the speech and then the intensity level of the background noise up or down in 2 dB steps until the MCL and accepted BNL were established.

The speech and background noise used to establish ANL scores were delivered by a Dell (OptiPlex GX 400) personal computer disc player routed through an audiometer into two loudspeakers. The loudspeakers were located equal distances from the subject (3 meters) at  $0^0$  and  $180^0$  azimuth in an audiometric booth (IAC, model #404A). A Cosmos recording of running male speech (Arizona Travelogue) was used as the primary stimulus and was presented at  $0^0$  azimuth. Multi-talker babble was used as the competing background noise and was presented at  $180^0$  azimuth.

Each subject participated in one trial period in which they were trained to perform the task. The starting level in determining the MCL was 30 dB HL at  $0^0$  azimuth. To obtain MCL for the right, left, and binaural modes, MCL was established 3 different times during the session. The verbal and written instructions for determining the MCL were as follows:

*You will listen to a story through a loudspeaker. After a few moments, select the loudness of the story that is most comfortable for you, as if listening to a radio. Hand-held buttons will allow you to make adjustments. First, turn the loudness up until it is too loud and then down until it is too soft. Finally, select the loudness level which is most comfortable for you.*

The background noise (multi-talker speech babble) was then added at  $180^0$  azimuth. The subjects adjusted the background noise to their maximum acceptable level.

The starting level of the background noise was also 30 dB HL. The subjects were given the following written and verbal instructions:

*You will now listen to the same story with background noise. After you have listened to this for a few moments, select the level of the background noise which you would be willing to accept or "put-up-with" without becoming tense or tired while following the story. First, turn the noise up until it is too loud and then down until the story becomes very clear. Finally, adjust the noise (up and down) to the level that you would "put-up-with" for a long time while following the story.*

After each trial, the level of the speech stimulus (e.g. 40 dB HL) and the background noise (e.g. 28 dB HL) was recorded. The level of the background noise was subtracted from the level of the speech to obtain ANL ( $\text{ANL} = 40 \text{ dB HL} - 28 \text{ dB HL} = 12 \text{ dB}$ ).

Monaural (right and left) and binaural ANL scores were established for both the omni-directional and directional microphone conditions. The two ANL scores (omni-directional and directional) were then subtracted from one another to obtain the ANL benefit score ( $\text{ANL benefit} = \text{omni-directional ANL} - \text{directional ANL}$ ) for each ear. When the ANL was determined monaurally, the non-test ear was plugged with a Howard Leight (NRP 33 / SNR 34 CE) pre-shaped foam earplug. In determining ANL scores, the MCL obtained in the omni-directional condition was also used for the directional condition. Pilot investigations showed no change in MCL for the omni-directional and directional microphone conditions (see Appendix C). The ANL procedure was performed a total of 7 times including 1 trial measure, 3 omni-directional measures (right, left, and binaural), 3 directional measures (right, left, and binaural). Estimated time of ANL testing was approximately 15 to 20 minutes or 2-3 minutes per measure.

### Speech Recognition Testing

Speech recognition thresholds (SRT) in noise (called masked SRT) were obtained by presenting spondee words (taken from Basic Auditory Tests: CD #101 R2, Auditec of Saint Louis) delivered at  $0^0$  azimuth at the MCL established for the ANL. Multi-talker babble, taken from the Revised Speech Perception in Noise test (Kalikow, Stevens, and Elliot, 1977), was used as the competing background noise and was presented at  $180^0$  azimuth. Using a modified version of the Tillman and Olsen (1973) procedure, the background noise was initially presented 30 dB below the subject's MCL. Spondee words were presented through a pre-recorded compact disc containing a spondee word list on one channel and multi-talker babble on the other channel. A Dell (OptiPlex GX 400) personal computer disc player routed through an audiometer into two loudspeakers was used to present the stimuli. If the subject correctly identified the spondee word, the BNL was increased by 10 dB until the subject missed two consecutive spondee words at the same level. At that time, the BNL was reduced by 10 dB (called the starting level), and pairs of spondee words were presented as the BNL was raised in 2 dB increments. If the subject missed 5 out of the first 6 words presented, the level of the background noise was reduced 6 dB below the starting level. Pairs of spondee words continued to be presented as the BNL was raised in 2dB increments until the subject missed 5 out of 6 words.

The masked SRT for each listening condition was established by adding the number of correct responses to the starting BNL and then subtracting one (half the number in which the BNL was being increased). After the masked SRT was obtained for both listening conditions, the directional masked SRT score was subtracted from the

omni-directional masked SRT score to obtain the masked SRT benefit score (masked SRT benefit = omni-directional masked SRT – directional masked SRT). Again, the non-test ear was plugged with a Howard Leight (NRP 33 / SNR 34 CE) pre-shaped foam earplug. The masked SRT procedure was preformed a total of 6 times. Estimated time of testing was approximately 30-35 minutes.

### Ear Canal Signal-to-Noise Ratio

The relative intensity level of the speech at MCL and accepted BNL was assessed for the omni-directional and the directional listening conditions using monaural and binaural ANL scores with an Audioscan RM500 computerized probe microphone system. The probe tube was placed near the plane of the subject's ear canal, and the speech and background noise were presented through the audiometer. The SPL at the tympanic membrane was measured for the following conditions:

- 1) aided MCL with the hearing aid in the omni-directional condition
- 2) aided speech babble noise adjusted to the “acceptable level” with the hearing aid in omni-directional condition
- 3) aided MCL with the hearing aid in the directional condition
- 4) aided speech babble noise adjusted to the “acceptable level” for the omni-directional condition with the hearing aid in directional condition.

This measure was preformed at the ANLs obtained for the monaural (right and left) and binaural modes. Each measure was replicated 4 times; therefore, a total of 32 probe tube measurements were obtained for each ear.

SNR data measured using the probe microphone system consisted of 65 data points measured in  $1/12^{\text{th}}$  octave steps over a frequency range of 200 Hz to 8000 Hz. All SNR data stored in the Audioscan RM500 was downloaded to a laptop PC by using the Audioscan RM500 XDATA32 extraction program. The program converted all data stored in the Audioscan RM500 into ASCII text files. The ASCII text files were then saved and stored as individual subject files in Microsoft Excel.

A point-by-point average from 200 to 5000 Hz was completed to give one number for the omni-directional MCL and BNL and one for the directional MCL and BNL both monaurally and binaurally. The BNL was then subtracted from the MCL resulting in one number for the omni-directional and directional conditions for each ear. The two remaining numbers (MCL – BNL for the omni-directional condition and MCL – BNL for the directional condition) were then subtracted from each other resulting in a benefit score. This number was referred to as the ear canal SNR (ear canal SNR benefit = directional ear canal SNR – omni-directional SNR). For the binaural condition, the right and left ear canal SNRs were combined to give one number.

#### APHAB Questionnaire Responses

Rather than rating impressions of listening with and without hearing aids, the APHAB questionnaire (see Appendix D) was modified to evaluate the effects of listening for the omni-directional and directional listening conditions. The following is an example of the types of situations the subjects were asked to rate: “when I am in a crowded grocery store, talking with the cashier, I can follow the conversation.” The subject was asked to rate this question on a five-point continuum from always to never

based on their impressions with their hearing aids in the omni-directional and directional conditions.

## CHAPTER IV

### Results

Descriptive statistics for ANL, masked SRT, and ear canal SNR are shown in Table 1. Tables 2-5 show descriptive statistics for ANL, masked SRT, and ear canal SNR for different types of circuits and microphone polar plots. Complete data for all subjects for all test conditions are shown in Appendices E-H. To compare the directional benefit among ANL, masked SRT, and ear canal SNR, a three-factor repeated measures ANOVA was computed (see Table 6) with criterion measure (ANL, masked SRT, and ear canal SNR), listening mode (monaural and binaural), and circuitry / polar plot grouping. Results from this ANOVA showed no significant main effects or interactions.

The effects of microphone directivity on the APHAB results (APHAB benefit shown in Table 7) were determined by computing a 2-way repeated measure ANOVA (see Table 8) with APHAB subtests (ease of communication, reverberation, background noise, and aversiveness to noise) and microphone directivity as the factors. The results from this ANOVA yielded a significant subtest by directivity interaction ( $F = 8.173$ ,  $p < .001$ ). To explore this interaction, paired t-tests were computed for each subtest. Results of these t-tests (see Table 9) showed the subtest Background Noise ( $t = 2.301$ ,  $p < .001$ ) was the only subtest significantly affected by directivity. Because four individual t-tests were completed, an alpha correction of  $.05 / 4$  (or  $.0125$ ) was used.

To determine if there was a linear relationship between the APHAB and the other criterion measures (ANL, masked SRT, and ear canal SNR), Pearson product-moment correlation coefficients were computed. Results from these correlations are shown in a

matrix (see Table 10), which shows no significant correlations between APHAB and the benefit for any of the other measures.

Table 1: Means, Standard Deviations, and Ranges for ANL, Masked SRT, and Ear Canal SNR Benefit Scores (measured in decibels).

| Ear Tested              | ANL Benefit<br>N = 40 | Masked SRT Benefit<br>N = 40 | Ear Canal SNR Benefit<br>N = 40 |
|-------------------------|-----------------------|------------------------------|---------------------------------|
| <b>Right</b>            |                       |                              |                                 |
| Mean                    | 3.40                  | 3.35                         | 2.22                            |
| Standard Deviation      | 2.49                  | 2.71                         | 3.69                            |
| Range                   | -2 – 10               | -2 – 12                      | -6.69 – 10.36                   |
| <b>Left</b>             |                       |                              |                                 |
| Mean                    | 3.70                  | 2.70                         | 4.01                            |
| Standard Deviation      | 3.12                  | 3.03                         | 5.03                            |
| Range                   | -4 – 12               | -2 – 11                      | -5.25 – 18.70                   |
| <b>Binaural</b>         |                       |                              |                                 |
| Mean                    | 3.50                  | 3.65                         | 2.88                            |
| Standard Deviation      | 2.89                  | 2.61                         | 3.20                            |
| Range                   | -4 – 12               | -2 – 9                       | -2.38 – 10.92                   |
| <b>Average of Means</b> | <b>3.53</b>           | <b>3.23</b>                  | <b>3.04</b>                     |

Table 2: Means, Standard Deviations, and Ranges for ANL, Masked SRT, and Ear Canal SNR Benefit Scores Based on Circuitry (measured in decibels).

| Ear Tested              | ANL Benefit<br>Analog / Digital<br>N = 15 / N = 25 | Masked SRT Benefit<br>Analog / Digital<br>N = 15 / N = 25 | Ear Canal SNR Benefit<br>Analog / Digital<br>N = 15 / N = 25 |
|-------------------------|----------------------------------------------------|-----------------------------------------------------------|--------------------------------------------------------------|
| <b>Right</b>            |                                                    |                                                           |                                                              |
| Mean                    | 3.73 / 3.25                                        | 3.47 / 3.25                                               | 2.49 / 1.95                                                  |
| Standard Deviation      | 2.37 / 2.63                                        | 1.64 / 3.28                                               | 3.94 / 3.64                                                  |
| Range                   | 0 – 10 / -2 – 8                                    | 1 – 7 / -2 – 12                                           | -5.10–10.36 / -6.69–9.30                                     |
| <b>Left</b>             |                                                    |                                                           |                                                              |
| Mean                    | 4.67 / 3.00                                        | 3.20 / 2.46                                               | 4.72 / 3.58                                                  |
| Standard Deviation      | 3.52 / 2.77                                        | 2.81 / 3.23                                               | 5.41 / 4.96                                                  |
| Range                   | 2 – 12 / -4 – 8                                    | -1 – 11 / -2 – 8                                          | -.91–18.70 / -5.25–17.19                                     |
| <b>Binaural</b>         |                                                    |                                                           |                                                              |
| Mean                    | 3.47 / 3.58                                        | 3.60 / 3.71                                               | 3.51 / 2.49                                                  |
| Standard Deviation      | 2.77 / 3.06                                        | 2.87 / 2.55                                               | 3.75 / 2.81                                                  |
| Range                   | -4 – 8 / 0 – 12                                    | 0 – 9 / -2 – 9                                            | -2.38–10.92 / -2.20–9.16                                     |
| <b>Average of Means</b> | <b>3.96 / 3.28</b>                                 | <b>3.42 / 3.14</b>                                        | <b>3.57 / 2.67</b>                                           |

Table 3: Means, Standard Deviations, and Ranges for ANL Benefit Scores Based on Microphone Polar Plot (measured in decibels).

| Ear Tested              | ANL Benefit           |                         |                         |                    |
|-------------------------|-----------------------|-------------------------|-------------------------|--------------------|
|                         | Supercarioid<br>N = 2 | Hypercardioid<br>N = 22 | Bi-directional<br>N = 1 | Adaptive<br>N = 15 |
| Right                   |                       |                         |                         |                    |
| Mean                    | 2.00                  | 3.64                    | -2.00                   | 3.60               |
| Standard Deviation      | 2.83                  | 2.44                    | 0.00                    | 2.29               |
| Range                   | 0 – 4                 | 0 – 10                  | -2 – -2                 | 0 – 8              |
| Left                    |                       |                         |                         |                    |
| Mean                    | 1.00                  | 4.45                    | -4.00                   | 3.47               |
| Standard Deviation      | 1.41                  | 3.08                    | 0.00                    | 2.56               |
| Range                   | 0 – 2                 | 2 – 12                  | -4 – -4                 | -2 – 8             |
| Binaural                |                       |                         |                         |                    |
| Mean                    | 2.00                  | 3.45                    | 2.00                    | 3.87               |
| Standard Deviation      | 2.83                  | 3.22                    | 0.00                    | 2.56               |
| Range                   | 0 – 4                 | -4 – 12                 | 2 – 2                   | 0 – 10             |
| <b>Average of Means</b> | <b>1.67</b>           | <b>3.85</b>             | <b>-1.33</b>            | <b>3.65</b>        |

Table 4: Means, Standard Deviations, and Ranges for Masked SRT Benefit Scores Based on Microphone Polar Plot (measured in decibels).

| Ear Tested              | Masked SRT Benefit    |                         |                         |                    |
|-------------------------|-----------------------|-------------------------|-------------------------|--------------------|
|                         | Supercarioid<br>N = 2 | Hypercardioid<br>N = 22 | Bi-directional<br>N = 1 | Adaptive<br>N = 15 |
| Right                   |                       |                         |                         |                    |
| Mean                    | 5.00                  | 3.05                    | -2.00                   | 3.93               |
| Standard Deviation      | 0.00                  | 1.94                    | 0.00                    | 3.45               |
| Range                   | 5 – 5                 | 0 – 7                   | -2 – -2                 | 0 – 12             |
| Left                    |                       |                         |                         |                    |
| Mean                    | 4.00                  | 2.41                    | -2.00                   | 3.27               |
| Standard Deviation      | 0.00                  | 2.86                    | 0.00                    | 3.33               |
| Range                   | 4 – 4                 | -2 – 11                 | -2 – -2                 | -2 – 8             |
| Binaural                |                       |                         |                         |                    |
| Mean                    | 5.50                  | 3.41                    | -1.00                   | 4.07               |
| Standard Deviation      | 3.54                  | 2.74                    | 0.00                    | 2.12               |
| Range                   | 3 – 8                 | -2 – 9                  | -1 – -1                 | 0 – 9              |
| <b>Average of Means</b> | <b>4.83</b>           | <b>2.96</b>             | <b>-1.67</b>            | <b>3.76</b>        |

Table 5: Means, Standard Deviations, and Ranges for Ear Canal SNR Benefit Scores Based on Microphone Polar Plot (measured in decibels).

| Ear Tested              | Ear Canal SNR Benefit  |                         |                         |                    |
|-------------------------|------------------------|-------------------------|-------------------------|--------------------|
|                         | Supercardioid<br>N = 2 | Hypercardioid<br>N = 22 | Bi-directional<br>N = 1 | Adaptive<br>N = 15 |
| <b>Right</b>            |                        |                         |                         |                    |
| Mean                    | 1.74                   | 2.32                    | -.46                    | 2.16               |
| Standard Deviation      | 3.97                   | 3.56                    | 0.00                    | 4.20               |
| Range                   | -1.07 – 4.55           | -5.10 – 10.36           | -.46 – -.46             | -6.69 – 9.30       |
| <b>Left</b>             |                        |                         |                         |                    |
| Mean                    | .90                    | 4.52                    | -.05                    | 4.01               |
| Standard Deviation      | 1.35                   | 4.91                    | 0.00                    | 5.74               |
| Range                   | -.54 – 1.86            | -.91 – 18.70            | -.05 – -.05             | -5.25 – 17.19      |
| <b>Binaural</b>         |                        |                         |                         |                    |
| Mean                    | 1.96                   | 2.75                    | -2.09                   | 3.22               |
| Standard Deviation      | .38                    | 3.49                    | 0.00                    | 3.16               |
| Range                   | 1.69 – 2.23            | -2.38 – 10.92           | -2.09 – -2.09           | -2.20 – 9.16       |
| <b>Average of Means</b> | <b>1.53</b>            | <b>3.20</b>             | <b>-.87</b>             | <b>3.13</b>        |

Table 6: Three-Factor Repeated Measures ANOVA for Benefit Measures (ANL, Masked SRT, and Ear Canal SNR). No significant results found.

| Significant Effects | Type III Sum of Squares | Degrees of Freedom | F-Value | Significance |
|---------------------|-------------------------|--------------------|---------|--------------|
| Ear                 | .976                    | 1                  | .232    | .633         |
| Measure             | 22.274                  | 2                  | 1.501   | .230         |
| Circuit/Polar Plot  | 54.730                  | 3                  | .517    | .673         |

Table 7: Means, Standard Deviations, and Ranges for APHAB Subtest Benefit Scores (measured in percent).

| APHAB Subtest         | Mean  | Standard Deviation | Range          |
|-----------------------|-------|--------------------|----------------|
| Aversiveness to Sound | -.11  | 9.34               | -22.70 – 33.30 |
| Reverberation         | 3.72  | 11.07              | -14.50 – 35.50 |
| Background Noise      | 11.76 | 17.87              | -14.50 – 66.50 |
| Ease of Communication | 5.00  | 13.74              | -17.60 – 57.70 |

Table 8: Two-Factor Repeated Measures ANOVA for APHAB Subtest and Direction.

| Significant Effects | Type III Sum of Squares | Degrees of Freedom | F-Value | Significance |
|---------------------|-------------------------|--------------------|---------|--------------|
| Subtest             | 13315.628               | 2.373              | 10.543  | .000         |
| Direction           | 1929.139                | 1                  | 10.094  | .003         |
| Subtest x Direction | 1279.271                | 2.825              | 8.539   | .000         |

Table 9: Paired Sample T-test Results for APHAB Subtests including Omni-directional and Directional Scores (**alpha correction: significance < .0125**).

| Subtest               | t-Value | Degrees of Freedom | Significance |
|-----------------------|---------|--------------------|--------------|
| Ease of Communication | -.08    | 40                 | .941         |
| Reverberation         | 2.13    | 40                 | .039         |
| Background Noise      | 4.14    | 40                 | < .001       |
| Aversiveness to Sound | 2.30    | 40                 | .027         |

Table 10: Correlation Matrix Comparing APHAB Subtest Results and ANL, Masked SRT, and Ear Canal SNR Benefit.

|                       |                 | Ease of Communication Subtest | Reverberation Subtest | Background Noise Subtest | Aversiveness to Sound Subtest |
|-----------------------|-----------------|-------------------------------|-----------------------|--------------------------|-------------------------------|
| ANL Benefit           | Pearson         |                               |                       |                          |                               |
|                       | Correlation     | -.162                         | -.332*                | -.231                    | .069                          |
|                       | Sig. (2-tailed) | .317                          | .036                  | .152                     | .672                          |
| Masked SRT Benefit    | Pearson         |                               |                       |                          |                               |
|                       | Correlation     | -.244                         | -.194                 | -.192                    | .006                          |
|                       | Sig. (2-tailed) | .129                          | .230                  | .235                     | .973                          |
| Ear Canal SNR Benefit | Pearson         |                               |                       |                          |                               |
|                       | Correlation     | -.037                         | .204                  | -.171                    | .031                          |
|                       | Sig. (2-tailed) | .825                          | .213                  | .297                     | .851                          |

\*\* Correlation is significant at the 0.01 level (2-tailed).

\* Correlation is significant at the 0.05 level (2-tailed).

## CHAPTER V

### Discussion

Directional microphones in hearing aids amplify signals arriving from the front more than signals arriving from other directions. The net effect of this selective amplification is improvement in the SNR, which is termed directional benefit. Directional benefit has been quantified physically with sound field and ear canal SNR, perceptually with SRT and speech discrimination scores, and subjectively with informal and formal questionnaires. An additional method for quantifying the beneficial effects of directional microphones in hearing aids was evaluated in this investigation. This method is the acceptable noise level (ANL), which was developed by Nabelek et al. (1991).

Using 40 hearing aid wearers with directional microphones as subjects, results of this investigation showed that the mean directional benefit assessed with ANL, masked SRT, and ear canal SNR are not significantly different (Table 1). This suggests that directional benefit can be assessed using any of the criterion measures (ANL, masked SRT, and ear canal SNR). Statistical analysis also revealed that directional hearing aid benefit is not different between hearing aids with analog and digital circuits or different directional polar plots.

The average and range of directional microphone benefit found in this study are smaller than the manufacturer's published performance data usually measured with front-to-back ratios or directivity indices on Knowles Electronic Manikin for Acoustic Research (KEMAR). This leads to questions about the sensitivity of the measures used and/or the way they were used in the present investigation. It is possible that both the

measures used and the experimental paradigm were not be sufficiently sensitive to quantify directional hearing aid benefit, however, the results of this investigation show general agreement with previously reported data for hearing aid directional benefit.

Literature reports have shown large variation in hearing aid directional benefit (as measured by SRT procedures). Table 11 displays SNR benefit based on SRT scores. With the exception of Compton (2002), the SRT benefit means and ranges reported in the literature are similar to the SRT benefit scores obtained in the present investigation (i.e. mean SRT benefit = 3.23 dB). Compton (2002) obtained much higher directional benefit scores when using binaural KEMAR recordings to simulate hearing aid conditions with normal hearing subjects.

ANL, masked SRT, and ear canal SNR measurements were obtained for the right ear, left ear, and binaurally. The results showed no benefit significant difference for listening mode (right, left, or binaural), indicating that similar benefit is obtained whether directional benefit is assessed monaurally or binaurally.

In order to quantify directional benefit, subjects were tested with speech and background noise at  $0^{\circ}$  and  $180^{\circ}$  azimuth, respectively. For the behavioral procedures (ANL and masked SRT), the subjects “turned-up” the background noise to their maximum acceptable background noise level or threshold. As was expected with the ANL procedure, subjects accepted more background noise in the directional condition, which resulted in decreased ANL scores for the directional condition. A similar effect occurred with the masked SRT procedure. When the hearing aids were changed from the omni-directional to the directional condition, the subject repeated 50% of the spondaic

Table 11: Studies used to Measure SRT Benefit.

| Investigators                   | Speech Stimuli                                    | Competing Stimuli              | Noise Angle                            | Mean Benefit | Benefit Range |
|---------------------------------|---------------------------------------------------|--------------------------------|----------------------------------------|--------------|---------------|
| Gravel et al. (1999)<br>N = 20  | Pediatric Speech<br>Intelligibility<br>test words | Multi-talker<br>Noise          | 180 <sup>0</sup>                       | 4.7          | 2 – 12        |
| Preves et al. (1999)<br>N = 10  | HINT<br>Sentences                                 | Speech<br>Spectrum<br>Noise    | 115 <sup>0</sup> &<br>245 <sup>0</sup> | 2.8          | -.4 – 4.7     |
| Wouters et al. (1999)<br>N = 10 | Bi-syllabic<br>Words                              | Multi-talker<br>Noise          | 90 <sup>0</sup>                        | 3.3          | -9.8 – 3.6    |
| Valente et al. (2000)<br>N = 50 | HINT<br>Sentences                                 | Spectrally<br>Matched<br>Noise | 180 <sup>0</sup>                       | 3.5          | 2.7 – 12.4    |
| Compton (2002)<br>N = 20        | HINT<br>Sentences                                 | Restaurant<br>Noise            | 180 <sup>0</sup>                       | 8.6          | 4.1 – 12.7    |

words with more background noise; therefore, the masked SRT also decreased for the directional condition. Conversely, the ear canal SNR (a physical measure) increased for the directional condition. This occurred because in the ear canal SNR procedure, the speech and background noise are held constant while the microphone condition is changed from omni-directional to directional. When the directional condition is selected, the background noise decreases in relation to the speech, which results in an increase in the ear canal SNR. The benefit difference between the ANL, masked SRT, and ear canal SNR suggest that these techniques measure directional advantage differently; however, since benefit for all three measures is expressed as a difference, the overall benefit result is not different. This suggests that when measuring benefit, the ANL, masked SRT, and ear canal SNR could be used interchangeably (see Table 6 for ANOVA results).

For the APHAB questionnaire, the only significant difference between the omni-directional and directional scores was the background noise subtest, which suggests that the other subtests (ease of communication, reverberation, and aversiveness to sound) may not be sufficiently sensitive to evaluate hearing aid directivity. This may suggest that to effectively evaluate microphone directivity via questionnaires, more questions related to a specific area (i.e. background noise) should be included.

Directional benefit quantification was shown through the background noise subtest; however, none of the APHAB subtests correlated significantly with ANL, masked SRT, or ear canal SNR. This suggests that the APHAB alone may not be sufficient to show the beneficial effects of directional microphones in hearing aids.

### Clinical Implications

Results of this study have clinical implications regarding quantification of hearing aid benefit. These results show that directional benefit can be assessed with the ANL, masked SRT, and ear canal SNR paradigms. In comparison to the masked SRT, ear canal SNR, and APHAB, the ANL procedure was the quickest and easiest for both the examiner and subjects. To obtain the ANL, the listener selected the maximum acceptable background noise while following a story at their MCL. Conversely, when obtaining the masked SRT the subjects were required to repeat speech in the presence of background noise, which was frustrating to the subjects because of their reduced speech perception. Also, the ANL and masked SRT procedures required minimal equipment including an audiometer, sound-treated room, two loudspeakers, and the necessary speech and background noise stimuli. Obtaining and analyzing the ear canal SNR, however, required a probe microphone system, a data management program, and a personal computer. Also, due to the specificity of the questions on the APHAB, it cannot be administered on the same day the hearing aids are distributed; therefore, it cannot give the clinician immediate feedback regarding the benefit received by the hearing aid directional microphones.

### Conclusions

The data from this study indicates that hearing aid directional benefit can be assessed with a variety of clinical measures including ANL, masked SRT, and ear canal SNR. Similar directional benefit was also seen for the background noise subtest of the APHAB. Therefore, when quantifying directional benefit in hearing aids, the ANL

appears to be a viable alternative to the more established masked SRT, ear canal SNR, and APHAB questionnaire.

### Future Research

In this study, ear canal SNR was quantified in order to determine the in-situ effects of directional hearing aid benefit. The stimuli used to make these measurements were speech and speech-babble background noise. In order to determine if more reliable results can be obtained with a more consistent signal, future quantification of ear canal SNR should also include a sweep tone or broadband input signal.

This study showed that background noise is reduced by hearing aids with directional microphones. Additional studies should be conducted which examine the background noise reduction other amplifying devices such as frequency-modulated systems.

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## **APPENDICES**

## **APPENDIX A**

### **ANL Pilot Data**

**ANL Pilot Data**

| <b>Subject</b> | <b>Subject Hearing</b> | <b>0° Paradigm</b> | <b>180° Paradigm</b> | <b>ANL Difference</b> |
|----------------|------------------------|--------------------|----------------------|-----------------------|
| 001            | Pathological           | 10                 | 12                   | -2                    |
| 002            | Pathological           | 20                 | 18                   | 2                     |
| 003            | Pathological           | 6                  | 6                    | 0                     |
| 004            | Normal                 | 6                  | 6                    | 0                     |
| 005            | Normal                 | 0                  | -2                   | 2                     |
| <b>Mean:</b>   |                        | <b>8.4</b>         | <b>8</b>             | <b>0.4</b>            |

## **APPENDIX B**

### **Participant Consent Form**

## **INFORMED CONSENT STATEMENT**

### **Quantification of Directional Hearing Aid Benefit: Comparison of Acceptable Noise Level, Masked Speech Recognition Threshold, Ear Canal Signal-to-Noise Ratio and Abbreviated Profile of Hearing Aid Benefit**

You are invited to participate in a research study. The purpose of this study is to determine how much background noise you can accept while listening to a story with your hearing aids in omni-directional and directional programs. We would like to know if this acceptance is affected by directional hearing aids. If you participate in this study, the investigator will obtain information regarding your hearing aid fitting from your records at the UT Hearing Clinic or your audiologist.

#### **General Information**

There will be one session lasting approximately two hours. During this session, you will be asked to adjust the loudness of a story to your most comfortable listening level. Next, background noise of many people talking will be added to the story. You will be asked to adjust the noise to the highest level that you will be willing to accept when following the story without becoming tense or tired. You will also be asked to respond to a standard speech understanding in noise test and complete a questionnaire about your hearing aid benefit. With speech or noise introduced into your ear, eight measurements will be taken of your ear canal. All tests will be repeated with hearing aids in omni-directional and directional modes. You will be paid \$10.00 plus \$10.00 travel allowance after completion of this study. If you decide to stop participating in the study, you will be paid travel allowance only.

#### **Risks**

There are no known risks with this procedure.

#### **Benefits**

Results of this study should show the relationship between directional microphones and acceptance of background noise. Other than an increased understanding about background noise acceptance and directional microphone technology and compensation, there are no immediate, direct benefits to you from this study.

#### **Confidentiality**

The information in the study records will be kept confidential. Data will be stored securely and will be made available only to persons conducting the study unless you specifically give permission in writing to do otherwise. No reference will be made in oral or written reports, which could link you to this study.

#### **Contact**

If you have any questions at any time about the study or the procedures, you may contact the Co Investigator, Dr. Sam Burchfield, at 576 South Stadium Hall on the University of Tennessee, Knoxville campus or by phone at (865) 974-4123. If you have

any questions about your rights as a participant, contact the University of Tennessee Compliance Section of the Office of research at (865) 974-3466.

**Participation**

Your participation in this study is voluntary. You may decline to participate without penalty. If you decide to participate, you may withdraw at anytime, and it will not affect other services that you may receive from the University of Tennessee Hearing and Speech Center or any other benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed, you may request that your data be returned to you or destroyed.

I have read and understand the above information. I have received a copy of this form. I agree to participant in this study.

Participant's signature:\_\_\_\_\_

Date:\_\_\_\_\_

Investigator's signature:\_\_\_\_\_

Date:\_\_\_\_\_

Revised: 4/10/02

## **APPENDIX C**

### **MCL Pilot Data**

**MCL Pilot Data**

| <b>Subject</b> | <b>Omni-directional MCL</b> | <b>Directional MCL</b> | <b>MCL Difference</b> |
|----------------|-----------------------------|------------------------|-----------------------|
| 001            | 44                          | 48                     | 4                     |
| 002            | 35                          | 38                     | 3                     |
| 003            | 48                          | 48                     | 0                     |
| 004            | 40                          | 42                     | 2                     |
| 005            | 46                          | 48                     | 2                     |
| <b>Mean:</b>   | <b>42.6</b>                 | <b>44.8</b>            | <b>2.2</b>            |

## **APPENDIX D**

### **APHAB Questionnaire (Forms A and B)**

## ABBREVIATED PROFILE OF HEARING AID BENEFIT

A

NAME: \_\_\_\_\_ TODAY'S DATE: \_\_\_\_/\_\_\_\_/\_\_\_\_ DATE OF BIRTH: \_\_\_\_/\_\_\_\_/\_\_\_\_

Last First

ADDRESS: \_\_\_\_\_

TELEPHONE: (home) \_\_\_\_\_ (work) \_\_\_\_\_ SSN: \_\_\_\_\_

## HEARING AID EXPERIENCE:

- ☐ Less than 6 weeks  
☐ 6 weeks to 11 months  
☐ 1 to 10 years  
☐ Over 10 years

## DAILY HEARING AID USE

- ☐ Less than 1 hour per day  
☐ 1 to 4 hours per day  
☐ 4 to 8 hours per day  
☐ 8 to 16 hours per day

## EMPLOYMENT:

- ☐ Full-time  
☐ Part-time  
☐ Not employed outside the home, or retired

**INSTRUCTIONS:** Please circle the answers that come closest to your everyday experience. Notice that each choice includes a percentage. You can use this to help you decide on your answer. For example, if a statement is true about 75% of the time, circle "C" for that item. If you have not experienced the situation we describe, try to think of a similar situation that you have been in and respond for that situation. If you have no idea, leave that item blank.

- A Always (99%)  
 B Almost Always (87%)  
 C Generally (75%)  
 D Half-the-time (50%)  
 E Occasionally (25%)  
 F Seldom (12%)  
 G Never (1%)

Program #1 (Omni-Directional)Program #2 (Directional)

1. When I am in a crowded grocery store, talking with the cashier, I can follow the conversation..... A B C D E F G A B C D E F G
2. I miss a lot of information when I'm listening to a lecture..... A B C D E F G A B C D E F G
3. Unexpected sounds, like a smoke detector or alarm bell are uncomfortable..... A B C D E F G A B C D E F G
4. I have difficulty hearing a conversation when I'm with one of my family at home..... A B C D E F G A B C D E F G
5. I have trouble understanding the dialogue in a movie or at the theater..... A B C D E F G A B C D E F G
6. When I am listening to the news on the car radio, and family members are talking, I have trouble hearing the news..... A B C D E F G A B C D E F G
7. When I'm at the dinner table with several people, and am trying to have a conversation with one person, understanding speech is difficult..... A B C D E F G A B C D E F G
8. Traffic noises are too loud..... A B C D E F G A B C D E F G
9. When I am talking with someone across a large empty room, I understand the words..... A B C D E F G A B C D E F G

- A Always (99%)  
 B Almost Always (87%)  
 C Generally (75%)  
 D Half-the-time (50%)  
 E Occasionally (25%)  
 F Seldom (12%)  
 G Never (1%)

|                                                                                                                         | <u>Program #1 (Omni-Directional)</u> | <u>Program #2 (Directional)</u> |
|-------------------------------------------------------------------------------------------------------------------------|--------------------------------------|---------------------------------|
| 10. I can understand conversations even when several people are talking.....                                            | A B C D E F G                        | A B C D E F G                   |
| 11. The sounds of construction work are uncomfortably loud.....                                                         | A B C D E F G                        | A B C D E F G                   |
| 12. I have trouble understanding others when an air conditioner or fan is on.....                                       | A B C D E F G                        | A B C D E F G                   |
| 13. I have trouble understanding the dialogue in a movie or at the theater.....                                         | A B C D E F G                        | A B C D E F G                   |
| 14. Traffic noises are too loud.....                                                                                    | A B C D E F G                        | A B C D E F G                   |
| 15. When I am in a small office, interviewing or answering questions, I have difficulty following the conversation..... | A B C D E F G                        | A B C D E F G                   |
| 16. I miss a lot of information when I'm listening to a lecture.....                                                    | A B C D E F G                        | A B C D E F G                   |
| 17. I have to ask people to repeat themselves in one-on-one conversation in a quiet room.....                           | A B C D E F G                        | A B C D E F G                   |
| 18. Unexpected sounds, like a smoke detector or alarm bell are uncomfortable.....                                       | A B C D E F G                        | A B C D E F G                   |
| 19. I can follow the words of a sermon when listening to a religious service.....                                       | A B C D E F G                        | A B C D E F G                   |
| 20. When I am in a crowded grocery store, talking with the cashier, I can follow the conversation.....                  | A B C D E F G                        | A B C D E F G                   |
| 21. I can communicate with others when we are in a crowd.....                                                           | A B C D E F G                        | A B C D E F G                   |
| 22. The sound of screeching tires is uncomfortably loud.....                                                            | A B C D E F G                        | A B C D E F G                   |
| 23. I have difficulty hearing a conversation when I'm with one of my family at home.....                                | A B C D E F G                        | A B C D E F G                   |
| 24. When I am talking with someone across a large empty room, I understand the words.....                               | A B C D E F G                        | A B C D E F G                   |



## ABBREVIATED PROFILE OF HEARING AID BENEFIT

B

NAME: \_\_\_\_\_ TODAY'S DATE: \_\_\_\_/\_\_\_\_/\_\_\_\_ DATE OF BIRTH: \_\_\_\_/\_\_\_\_/\_\_\_\_

Last First

ADDRESS: \_\_\_\_\_

TELEPHONE: (home) \_\_\_\_\_ (work) \_\_\_\_\_ SSN: \_\_\_\_\_

## HEARING AID EXPERIENCE:

- ☐ Less than 6 weeks  
☐ 6 weeks to 11 months  
☐ 1 to 10 years  
☐ Over 10 years

## DAILY HEARING AID USE

- ☐ Less than 1 hour per day  
☐ 1 to 4 hours per day  
☐ 4 to 8 hours per day  
☐ 8 to 16 hours per day

## EMPLOYMENT:

- ☐ Full-time  
☐ Part-time  
☐ Not employed outside the home, or retired

**INSTRUCTIONS:** Please circle the answers that come closest to your everyday experience. Notice that each choice includes a percentage. You can use this to help you decide on your answer. For example, if a statement is true about 75% of the time, circle "C" for that item. If you have not experienced the situation we describe, try to think of a similar situation that you have been in and respond for that situation. If you have no idea, leave that item blank.

- A Always (99%)  
 B Almost Always (87%)  
 C Generally (75%)  
 D Half-the-time (50%)  
 E Occasionally (25%)  
 F Seldom (12%)  
 G Never (1%)

Program #1 (Omni-Directional)    Program #2 (Directional)

1. The sound of a fire engine siren close by is so loud that I need to cover my ears..... A B C D E F G A B C D E F G
2. When a speaker is addressing a small group, and everyone is listening quietly, I have to strain to understand..... A B C D E F G A B C D E F G
3. It's hard for me to understand what is being said at lectures or church services..... A B C D E F G A B C D E F G
4. When I'm at the dinner table with several people, and am trying to have a conversation with one person, understanding speech is difficult..... A B C D E F G A B C D E F G
5. When I am in a theater watching a movie or play, and the people around me are whispering and rustling paper wrappers, I can still make out the dialogue..... A B C D E F G A B C D E F G
6. When I'm in a quiet conversation with my doctor in an examination room, it is hard to follow the conversation..... A B C D E F G A B C D E F G
7. When I am listening to the news on the car radio, and family members are talking, I have trouble hearing the news..... A B C D E F G A B C D E F G
8. The sounds of running water, such as a toilet or shower, are uncomfortably loud..... A B C D E F G A B C D E F G
9. When I am having a quiet conversation with a friend, I have difficulty understanding..... A B C D E F G A B C D E F G

- A Always (99%)  
 B Almost Always (87%)  
 C Generally (75%)  
 D Half-the-time (50%)  
 E Occasionally (25%)  
 F Seldom (12%)  
 G Never (1%)

Program #1 (Omni-Directional)    Program #2 (Directional)

- |                                                                                                                                                                  |               |               |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------|---------------|
| 10. When I am in a small office, interviewing or answering questions, I have difficulty following the conversation.....                                          | A B C D E F G | A B C D E F G |
| 11. When I am in a theater watching a movie or play, and the people around me are whispering and rustling paper wrappers, I can still make out the dialogue..... | A B C D E F G | A B C D E F G |
| 12. When I am having a quiet conversation with a friend, I have difficulty understanding.....                                                                    | A B C D E F G | A B C D E F G |
| 13. The sounds of running water, such as a toilet or shower, are uncomfortably loud.....                                                                         | A B C D E F G | A B C D E F G |
| 14. When a speaker is addressing a small group, and everyone is listening quietly, I have to strain to understand.....                                           | A B C D E F G | A B C D E F G |
| 15. When I'm in a quiet conversation with my doctor in an examination room, it is hard to follow the conversation.....                                           | A B C D E F G | A B C D E F G |
| 16. I can understand conversations even when several people are talking.....                                                                                     | A B C D E F G | A B C D E F G |
| 17. The sounds of construction work are uncomfortably loud.....                                                                                                  | A B C D E F G | A B C D E F G |
| 18. It's hard for me to understand what is being said at lectures or church services.....                                                                        | A B C D E F G | A B C D E F G |
| 19. I can communicate with others when we are in a crowd.....                                                                                                    | A B C D E F G | A B C D E F G |
| 20. The sound of a fire engine siren close by is so loud that I need to cover my ears.....                                                                       | A B C D E F G | A B C D E F G |
| 21. I can follow the words of a sermon when listening to a religious service.....                                                                                | A B C D E F G | A B C D E F G |
| 22. The sound of screeching tires is uncomfortably loud.....                                                                                                     | A B C D E F G | A B C D E F G |
| 23. I have to ask people to repeat themselves in one-on-one conversation in a quiet room.....                                                                    | A B C D E F G | A B C D E F G |
| 24. I have trouble understanding others when an air conditioner or fan is on.....                                                                                | A B C D E F G | A B C D E F G |



## **APPENDIX E**

### **Individual ANL Participant Data**

**ANL Subject Data for Right, Monaural Mode**

| Subject      | <u>Right Omnidirectional</u><br>ANL Scores |             |            | <u>Right Directional</u><br>ANL Scores |             |            | Benefit    |
|--------------|--------------------------------------------|-------------|------------|----------------------------------------|-------------|------------|------------|
|              | MCL                                        | BNL         | ANL        | MCL                                    | BNL         | ANL        |            |
| 001          | 50                                         | 46          | 4          | 50                                     | 46          | 4          | 0          |
| 002          | 56                                         | 48          | 8          | 56                                     | 50          | 6          | 2          |
| 003          | 40                                         | 36          | 4          | 40                                     | 38          | 2          | 2          |
| 004          | 52                                         | 46          | 6          | 52                                     | 50          | 2          | 4          |
| 005          | 34                                         | 24          | 10         | 34                                     | 30          | 4          | 6          |
| 006          | 50                                         | 44          | 6          | 50                                     | 46          | 4          | 2          |
| 007          | 48                                         | 38          | 10         | 48                                     | 40          | 8          | 2          |
| 008          | 76                                         | 66          | 10         | 76                                     | 72          | 4          | 6          |
| 009          | 66                                         | 60          | 6          | 66                                     | 66          | 0          | 6          |
| 010          | 28                                         | 28          | 0          | 28                                     | 26          | 2          | -2         |
| 011          | 48                                         | 28          | 20         | 48                                     | 32          | 16         | 4          |
| 012          | 68                                         | 48          | 20         | 68                                     | 50          | 18         | 2          |
| 013          | 44                                         | 36          | 8          | 44                                     | 36          | 8          | 0          |
| 014          | 46                                         | 32          | 14         | 46                                     | 42          | 4          | 10         |
| 015          | 46                                         | 34          | 12         | 46                                     | 34          | 12         | 0          |
| 016          | 70                                         | 52          | 18         | 70                                     | 60          | 10         | 8          |
| 017          | 62                                         | 56          | 6          | 62                                     | 58          | 4          | 2          |
| 018          | 40                                         | 34          | 6          | 40                                     | 36          | 4          | 2          |
| 019          | 72                                         | 66          | 6          | 72                                     | 72          | 0          | 6          |
| 020          | 48                                         | 40          | 8          | 48                                     | 40          | 8          | 0          |
| 021          | 56                                         | 44          | 12         | 56                                     | 46          | 10         | 2          |
| 022          | 34                                         | 20          | 14         | 34                                     | 24          | 10         | 4          |
| 023          | 44                                         | 38          | 6          | 44                                     | 40          | 4          | 2          |
| 024          | 46                                         | 46          | 0          | 46                                     | 46          | 0          | 0          |
| 025          | 46                                         | 42          | 4          | 46                                     | 46          | 0          | 4          |
| 026          | 36                                         | 32          | 4          | 36                                     | 36          | 0          | 4          |
| 027          | 54                                         | 50          | 4          | 54                                     | 54          | 0          | 4          |
| 028          | 40                                         | 32          | 8          | 40                                     | 34          | 6          | 2          |
| 029          | 42                                         | 36          | 6          | 42                                     | 40          | 2          | 4          |
| 030          | 62                                         | 54          | 8          | 62                                     | 56          | 6          | 2          |
| 031          | 52                                         | 46          | 6          | 52                                     | 52          | 0          | 6          |
| 032          | 48                                         | 40          | 8          | 48                                     | 44          | 4          | 4          |
| 033          | 54                                         | 55          | 10         | 54                                     | 48          | 6          | 4          |
| 034          | 50                                         | 44          | 6          | 50                                     | 48          | 2          | 4          |
| 035          | 54                                         | 48          | 6          | 54                                     | 50          | 4          | 2          |
| 036          | 44                                         | 36          | 8          | 44                                     | 40          | 4          | 4          |
| 037          | 56                                         | 50          | 6          | 56                                     | 58          | -2         | 8          |
| 038          | 56                                         | 48          | 8          | 56                                     | 52          | 4          | 4          |
| 039          | 54                                         | 46          | 8          | 54                                     | 52          | 2          | 6          |
| 040          | 44                                         | 36          | 6          | 44                                     | 42          | 2          | 4          |
| <b>Mean:</b> | <b>50.4</b>                                | <b>42.6</b> | <b>8.0</b> | <b>50.4</b>                            | <b>45.8</b> | <b>4.6</b> | <b>3.4</b> |

## ANL Subject Data for Left, Monaural Mode

| Subject      | <u>Left Omni-directional</u><br>ANL Scores |             |            | <u>Left Directional</u><br>ANL Scores |             |            | Benefit    |
|--------------|--------------------------------------------|-------------|------------|---------------------------------------|-------------|------------|------------|
|              | MCL                                        | BNL         | ANL        | MCL                                   | BNL         | ANL        |            |
| 001          | 50                                         | 44          | 6          | 50                                    | 44          | 6          | 0          |
| 002          | 52                                         | 44          | 8          | 52                                    | 50          | 2          | 6          |
| 003          | 44                                         | 38          | 6          | 44                                    | 42          | 2          | 4          |
| 004          | 62                                         | 50          | 12         | 62                                    | 58          | 4          | 8          |
| 005          | 30                                         | 24          | 6          | 30                                    | 26          | 4          | 2          |
| 006          | 56                                         | 48          | 8          | 56                                    | 54          | 2          | 6          |
| 007          | 46                                         | 38          | 8          | 46                                    | 38          | 8          | 0          |
| 008          | 66                                         | 56          | 10         | 66                                    | 68          | -2         | 12         |
| 009          | 66                                         | 64          | 2          | 66                                    | 68          | -2         | 4          |
| 010          | 28                                         | 22          | 6          | 28                                    | 18          | 10         | -4         |
| 011          | 48                                         | 28          | 20         | 48                                    | 30          | 18         | 2          |
| 012          | 64                                         | 48          | 16         | 64                                    | 50          | 14         | 2          |
| 013          | 46                                         | 36          | 10         | 46                                    | 38          | 8          | 2          |
| 014          | 46                                         | 30          | 16         | 46                                    | 42          | 4          | 12         |
| 015          | 48                                         | 26          | 22         | 48                                    | 28          | 20         | 2          |
| 016          | 66                                         | 50          | 16         | 66                                    | 56          | 10         | 6          |
| 017          | 66                                         | 62          | 4          | 66                                    | 64          | 2          | 2          |
| 018          | 56                                         | 48          | 8          | 56                                    | 54          | 2          | 6          |
| 019          | 74                                         | 66          | 8          | 74                                    | 70          | 4          | 4          |
| 020          | 42                                         | 32          | 10         | 42                                    | 36          | 6          | 4          |
| 021          | 36                                         | 28          | 8          | 36                                    | 30          | 6          | 2          |
| 022          | 38                                         | 24          | 14         | 38                                    | 28          | 10         | 4          |
| 023          | 48                                         | 42          | 6          | 48                                    | 44          | 4          | 2          |
| 024          | 44                                         | 38          | 6          | 44                                    | 38          | 2          | 4          |
| 025          | 48                                         | 46          | 2          | 48                                    | 48          | 0          | 2          |
| 026          | 40                                         | 34          | 6          | 40                                    | 36          | 4          | 2          |
| 027          | 52                                         | 44          | 8          | 52                                    | 50          | 2          | 6          |
| 028          | 46                                         | 40          | 6          | 46                                    | 42          | 4          | 2          |
| 029          | 48                                         | 40          | 8          | 48                                    | 38          | 10         | -2         |
| 030          | 60                                         | 50          | 10         | 60                                    | 54          | 6          | 4          |
| 031          | 54                                         | 46          | 8          | 54                                    | 52          | 2          | 6          |
| 032          | 48                                         | 40          | 8          | 48                                    | 46          | 2          | 6          |
| 033          | 60                                         | 48          | 12         | 60                                    | 56          | 4          | 8          |
| 034          | 50                                         | 42          | 8          | 50                                    | 48          | 2          | 6          |
| 035          | 54                                         | 48          | 6          | 54                                    | 50          | 4          | 2          |
| 036          | 38                                         | 36          | 2          | 38                                    | 38          | 0          | 2          |
| 037          | 52                                         | 50          | 2          | 52                                    | 54          | -2         | 4          |
| 038          | 60                                         | 52          | 8          | 60                                    | 54          | 6          | 2          |
| 039          | 62                                         | 56          | 6          | 62                                    | 58          | 4          | 2          |
| 040          | 46                                         | 38          | 8          | 46                                    | 42          | 4          | 4          |
| <b>Mean:</b> | <b>51.0</b>                                | <b>42.4</b> | <b>8.6</b> | <b>51.0</b>                           | <b>46.0</b> | <b>4.9</b> | <b>3.7</b> |

**ANL Subject Data for Binaural Mode**

| Subject      | <u>Binaural Omni-directional</u><br>ANL Scores |             |             | <u>Binaural Directional</u><br>ANL Scores |             |             | Benefit    |
|--------------|------------------------------------------------|-------------|-------------|-------------------------------------------|-------------|-------------|------------|
|              | MCL                                            | BNL         | ANL         | MCL                                       | BNL         | ANL         |            |
| 001          | 46                                             | 42          | 4           | 46                                        | 42          | 4           | 0          |
| 002          | 54                                             | 50          | 4           | 54                                        | 56          | -2          | 6          |
| 003          | 42                                             | 38          | 4           | 42                                        | 40          | 2           | 2          |
| 004          | 54                                             | 46          | 8           | 54                                        | 54          | 0           | 8          |
| 005          | 32                                             | 26          | 6           | 32                                        | 28          | 4           | 2          |
| 006          | 46                                             | 44          | 2           | 46                                        | 46          | 0           | 2          |
| 007          | 42                                             | 32          | 10          | 42                                        | 36          | 6           | 4          |
| 008          | 52                                             | 42          | 10          | 52                                        | 48          | 4           | 6          |
| 009          | 54                                             | 50          | 4           | 54                                        | 52          | 2           | 2          |
| 010          | 36                                             | 28          | 8           | 36                                        | 30          | 6           | 2          |
| 011          | 42                                             | 24          | 18          | 42                                        | 28          | 14          | 4          |
| 012          | 60                                             | 46          | 14          | 60                                        | 50          | 10          | 4          |
| 013          | 46                                             | 34          | 12          | 46                                        | 38          | 8           | 4          |
| 014          | 42                                             | 28          | 14          | 42                                        | 32          | 10          | 4          |
| 015          | 46                                             | 32          | 14          | 46                                        | 32          | 14          | 0          |
| 016          | 62                                             | 46          | 16          | 62                                        | 58          | 4           | 12         |
| 017          | 58                                             | 54          | 4           | 58                                        | 58          | 0           | 4          |
| 018          | 30                                             | 28          | 2           | 30                                        | 30          | 0           | 2          |
| 019          | 64                                             | 58          | 6           | 64                                        | 62          | 2           | 4          |
| 020          | 46                                             | 34          | 12          | 46                                        | 36          | 10          | 2          |
| 021          | 38                                             | 34          | 4           | 38                                        | 30          | 8           | -4         |
| 022          | 38                                             | 26          | 12          | 38                                        | 30          | 8           | 4          |
| 023          | 46                                             | 36          | 10          | 46                                        | 40          | 6           | 4          |
| 024          | 46                                             | 44          | 2           | 46                                        | 48          | -2          | 4          |
| 025          | 42                                             | 42          | 0           | 42                                        | 46          | -4          | 4          |
| 026          | 38                                             | 34          | 4           | 38                                        | 38          | 0           | 4          |
| 027          | 50                                             | 50          | 0           | 50                                        | 56          | -6          | 6          |
| 028          | 46                                             | 44          | 2           | 46                                        | 44          | 2           | 0          |
| 029          | 46                                             | 36          | 10          | 46                                        | 36          | 10          | 0          |
| 030          | 56                                             | 46          | 10          | 56                                        | 50          | 6           | 4          |
| 031          | 50                                             | 42          | 8           | 50                                        | 50          | 0           | 8          |
| 032          | 42                                             | 38          | 4           | 42                                        | 42          | 0           | 4          |
| 033          | 50                                             | 40          | 10          | 50                                        | 46          | 4           | 6          |
| 034          | 48                                             | 44          | 4           | 48                                        | 46          | 2           | 2          |
| 035          | 50                                             | 46          | 4           | 50                                        | 46          | 4           | 0          |
| 036          | 44                                             | 36          | 8           | 44                                        | 38          | 6           | 2          |
| 037          | 54                                             | 46          | 8           | 54                                        | 56          | -2          | 10         |
| 038          | 60                                             | 52          | 8           | 60                                        | 54          | 6           | 2          |
| 039          | 54                                             | 48          | 6           | 54                                        | 52          | 2           | 4          |
| 040          | 46                                             | 42          | 4           | 46                                        | 44          | 2           | 2          |
| <b>Mean:</b> | <b>47.5</b>                                    | <b>40.2</b> | <b>7.25</b> | <b>47.5</b>                               | <b>43.7</b> | <b>3.75</b> | <b>3.5</b> |

## **APPENDIX F**

### **Individual Masked SRT Participant Data**

## Masked SRT Subject Data for Right, Monaural Mode

| Subject      | <u>Right Omni-directional</u><br>SRT Scores |             |             | <u>Right Directional</u><br>SRT Scores |             |             | Benefit    |
|--------------|---------------------------------------------|-------------|-------------|----------------------------------------|-------------|-------------|------------|
|              | MCL                                         | SRT BNL     | SRT Diff.   | MCL                                    | SRT BNL     | SRT Diff.   |            |
| 001          | 50                                          | 52          | -2          | 50                                     | 57          | -7          | 5          |
| 002          | 56                                          | 57          | -1          | 56                                     | 63          | -7          | 6          |
| 003          | 40                                          | 40          | 0           | 40                                     | 40          | 0           | 0          |
| 004          | 52                                          | 48          | 4           | 52                                     | 52          | 0           | 4          |
| 005          | 34                                          | 36          | -2          | 34                                     | 36          | -2          | 0          |
| 006          | 50                                          | 55          | -5          | 50                                     | 59          | -9          | 4          |
| 007          | 48                                          | 49          | -1          | 48                                     | 59          | -11         | 10         |
| 008          | 76                                          | 77          | -1          | 76                                     | 80          | -4          | 3          |
| 009          | 66                                          | 73          | -7          | 66                                     | 73          | -7          | 0          |
| 010          | 28                                          | 29          | -1          | 28                                     | 27          | 1           | -2         |
| 011          | 48                                          | 50          | -2          | 48                                     | 51          | -3          | 1          |
| 012          | 68                                          | 69          | -1          | 68                                     | 69          | -1          | 0          |
| 013          | 44                                          | 49          | -5          | 44                                     | 54          | -10         | 5          |
| 014          | 46                                          | 51          | -5          | 46                                     | 56          | -10         | 5          |
| 015          | 46                                          | 53          | -7          | 46                                     | 53          | -7          | 0          |
| 016          | 70                                          | 61          | 9           | 70                                     | 63          | 7           | 2          |
| 017          | 62                                          | 69          | -7          | 62                                     | 73          | -11         | 4          |
| 018          | 40                                          | 44          | -4          | 40                                     | 49          | -9          | 5          |
| 019          | 72                                          | 83          | -11         | 72                                     | 87          | -15         | 4          |
| 020          | 48                                          | 59          | -11         | 48                                     | 62          | -14         | 3          |
| 021          | 56                                          | 58          | -2          | 56                                     | 59          | -3          | 1          |
| 022          | 34                                          | 27          | 7           | 34                                     | 29          | 5           | 2          |
| 023          | 44                                          | 43          | 1           | 44                                     | 45          | -1          | 2          |
| 024          | 46                                          | 54          | -8          | 46                                     | 57          | -11         | 3          |
| 025          | 46                                          | 52          | -6          | 46                                     | 57          | -11         | 5          |
| 026          | 36                                          | 47          | -11         | 36                                     | 52          | -16         | 5          |
| 027          | 54                                          | 52          | 2           | 54                                     | 57          | -3          | 5          |
| 028          | 40                                          | 44          | -4          | 40                                     | 44          | -4          | 0          |
| 029          | 42                                          | 50          | -8          | 42                                     | 54          | -12         | 4          |
| 030          | 62                                          | 68          | -6          | 62                                     | 71          | -9          | 3          |
| 031          | 52                                          | 57          | -5          | 52                                     | 60          | -8          | 3          |
| 032          | 48                                          | 54          | -6          | 48                                     | 58          | -10         | 4          |
| 033          | 54                                          | 62          | -8          | 54                                     | 67          | -13         | 5          |
| 034          | 50                                          | 53          | -3          | 50                                     | 55          | -5          | 2          |
| 035          | 54                                          | 63          | -9          | 54                                     | 64          | -10         | 1          |
| 036          | 44                                          | 49          | -5          | 44                                     | 52          | -8          | 3          |
| 037          | 56                                          | 56          | 0           | 56                                     | 68          | -12         | 12         |
| 038          | 56                                          | 58          | -2          | 56                                     | 61          | -5          | 3          |
| 039          | 54                                          | 53          | 1           | 54                                     | 60          | -6          | 7          |
| 040          | 44                                          | 49          | -5          | 44                                     | 54          | -10         | 5          |
| <b>Mean:</b> | <b>50.4</b>                                 | <b>53.8</b> | <b>-3.4</b> | <b>50.4</b>                            | <b>57.2</b> | <b>-6.8</b> | <b>3.4</b> |

**Masked SRT Subject Data for Left, Monaural Mode**

| Subject      | <u>Left Omni-directional</u><br><u>SRT Scores</u> |             |             | <u>Left Directional</u><br><u>SRT Scores</u> |             |             | Benefit    |
|--------------|---------------------------------------------------|-------------|-------------|----------------------------------------------|-------------|-------------|------------|
|              | MCL                                               | SRT BNL     | SRT Diff.   | MCL                                          | SRT BNL     | SRT Diff.   |            |
| 001          | 50                                                | 52          | -2          | 50                                           | 56          | -6          | 4          |
| 002          | 52                                                | 56          | -4          | 52                                           | 60          | -8          | 4          |
| 003          | 44                                                | 47          | -3          | 44                                           | 48          | -4          | 1          |
| 004          | 62                                                | 61          | 1           | 62                                           | 72          | -10         | 11         |
| 005          | 30                                                | 37          | -7          | 30                                           | 38          | -8          | 1          |
| 006          | 56                                                | 59          | -3          | 56                                           | 60          | -4          | 1          |
| 007          | 46                                                | 51          | -5          | 46                                           | 54          | -8          | 3          |
| 008          | 66                                                | 71          | -5          | 66                                           | 72          | -6          | 1          |
| 009          | 66                                                | 71          | -5          | 66                                           | 71          | -5          | 0          |
| 010          | 28                                                | 27          | 1           | 28                                           | 25          | 3           | -2         |
| 011          | 48                                                | 53          | -5          | 48                                           | 51          | -3          | -2         |
| 012          | 64                                                | 66          | -2          | 64                                           | 66          | -2          | 0          |
| 013          | 46                                                | 51          | -5          | 46                                           | 59          | -13         | 8          |
| 014          | 46                                                | 44          | 2           | 46                                           | 48          | -2          | 4          |
| 015          | 48                                                | 50          | -2          | 48                                           | 53          | -5          | 3          |
| 016          | 66                                                | 61          | 5           | 66                                           | 62          | 4           | 1          |
| 017          | 66                                                | 73          | -7          | 66                                           | 75          | -9          | 2          |
| 018          | 56                                                | 55          | 1           | 56                                           | 63          | -7          | 8          |
| 019          | 74                                                | 73          | 1           | 74                                           | 74          | 0           | 1          |
| 020          | 42                                                | 48          | -6          | 42                                           | 51          | -9          | 3          |
| 021          | 36                                                | 33          | 3           | 36                                           | 36          | 0           | 3          |
| 022          | 38                                                | 40          | -2          | 38                                           | 44          | -6          | 4          |
| 023          | 48                                                | 43          | 5           | 48                                           | 49          | -1          | 6          |
| 024          | 44                                                | 48          | -4          | 44                                           | 55          | -11         | 7          |
| 025          | 48                                                | 58          | -10         | 48                                           | 62          | -14         | 4          |
| 026          | 40                                                | 50          | -10         | 40                                           | 49          | -9          | -1         |
| 027          | 52                                                | 53          | -1          | 52                                           | 58          | -6          | 5          |
| 028          | 46                                                | 52          | -6          | 46                                           | 50          | -4          | -2         |
| 029          | 48                                                | 50          | -2          | 48                                           | 52          | -4          | 2          |
| 030          | 60                                                | 63          | -3          | 60                                           | 67          | -7          | 4          |
| 031          | 54                                                | 56          | -2          | 54                                           | 61          | -7          | 5          |
| 032          | 48                                                | 52          | -4          | 48                                           | 54          | -6          | 2          |
| 033          | 60                                                | 61          | -1          | 60                                           | 66          | -6          | 5          |
| 034          | 50                                                | 53          | -3          | 50                                           | 61          | -11         | 8          |
| 035          | 54                                                | 57          | -3          | 54                                           | 58          | -4          | 1          |
| 036          | 38                                                | 44          | -6          | 38                                           | 42          | -4          | -2         |
| 037          | 52                                                | 58          | -6          | 52                                           | 58          | -6          | 0          |
| 038          | 60                                                | 64          | -4          | 60                                           | 66          | -6          | 2          |
| 039          | 62                                                | 65          | -3          | 62                                           | 66          | -4          | 1          |
| 040          | 46                                                | 53          | -7          | 46                                           | 55          | -9          | 2          |
| <b>Mean:</b> | <b>51.0</b>                                       | <b>54.0</b> | <b>-3.0</b> | <b>51</b>                                    | <b>56.7</b> | <b>-5.7</b> | <b>2.7</b> |

**Masked SRT Subject Data for Binaural Mode**

| Subject      | <u>Binaural Omni-directional</u><br><u>SRT Scores</u> |             |             | <u>Binaural Directional</u><br><u>SRT Scores</u> |             |              | Benefit    |
|--------------|-------------------------------------------------------|-------------|-------------|--------------------------------------------------|-------------|--------------|------------|
|              | MCL                                                   | SRT BNL     | SRT Diff.   | MCL                                              | SRT BNL     | SRT Diff.    |            |
| 001          | 46                                                    | 54          | -8          | 46                                               | 57          | -11          | 3          |
| 002          | 54                                                    | 61          | -7          | 54                                               | 67          | -13          | 6          |
| 003          | 42                                                    | 46          | -4          | 42                                               | 49          | -7           | 3          |
| 004          | 54                                                    | 60          | -6          | 54                                               | 69          | -15          | 9          |
| 005          | 32                                                    | 38          | -6          | 32                                               | 44          | -12          | 6          |
| 006          | 46                                                    | 56          | -10         | 46                                               | 59          | -13          | 3          |
| 007          | 42                                                    | 44          | -2          | 42                                               | 48          | -6           | 4          |
| 008          | 52                                                    | 58          | -6          | 52                                               | 66          | -14          | 8          |
| 009          | 54                                                    | 64          | -10         | 54                                               | 66          | -12          | 2          |
| 010          | 36                                                    | 44          | -8          | 26                                               | 43          | -7           | -1         |
| 011          | 42                                                    | 47          | -5          | 42                                               | 49          | -7           | 2          |
| 012          | 60                                                    | 63          | -3          | 60                                               | 67          | -7           | 4          |
| 013          | 46                                                    | 56          | -10         | 46                                               | 61          | -15          | 5          |
| 014          | 42                                                    | 47          | -5          | 42                                               | 49          | -7           | 2          |
| 015          | 46                                                    | 52          | -6          | 46                                               | 56          | -10          | 4          |
| 016          | 62                                                    | 63          | -1          | 62                                               | 68          | -6           | 5          |
| 017          | 58                                                    | 67          | -9          | 58                                               | 71          | -13          | 4          |
| 018          | 30                                                    | 42          | -12         | 30                                               | 42          | -12          | 0          |
| 019          | 64                                                    | 77          | -13         | 64                                               | 80          | -16          | 3          |
| 020          | 46                                                    | 59          | -13         | 46                                               | 61          | -15          | 2          |
| 021          | 38                                                    | 40          | -2          | 38                                               | 40          | -2           | 0          |
| 022          | 38                                                    | 42          | -4          | 38                                               | 49          | -11          | 7          |
| 023          | 46                                                    | 50          | -4          | 46                                               | 52          | -6           | 2          |
| 024          | 46                                                    | 52          | -6          | 46                                               | 57          | -11          | 5          |
| 025          | 42                                                    | 48          | -6          | 42                                               | 56          | -14          | 8          |
| 026          | 38                                                    | 53          | -15         | 38                                               | 57          | -19          | 4          |
| 027          | 50                                                    | 51          | -1          | 50                                               | 57          | -7           | 6          |
| 028          | 50                                                    | 50          | 0           | 50                                               | 48          | 2            | -2         |
| 029          | 46                                                    | 53          | -7          | 46                                               | 55          | -9           | 2          |
| 030          | 56                                                    | 63          | -7          | 56                                               | 63          | -7           | 0          |
| 031          | 50                                                    | 55          | -5          | 50                                               | 59          | -9           | 4          |
| 032          | 42                                                    | 41          | -9          | 42                                               | 55          | -13          | 4          |
| 033          | 50                                                    | 58          | -8          | 50                                               | 63          | -13          | 5          |
| 034          | 48                                                    | 52          | -4          | 48                                               | 58          | -10          | 6          |
| 035          | 50                                                    | 58          | -8          | 50                                               | 58          | -8           | 0          |
| 036          | 44                                                    | 50          | -6          | 44                                               | 53          | -9           | 3          |
| 037          | 54                                                    | 60          | -6          | 54                                               | 69          | -15          | 9          |
| 038          | 60                                                    | 61          | -1          | 60                                               | 63          | -3           | 2          |
| 039          | 54                                                    | 60          | -6          | 54                                               | 64          | -10          | 4          |
| 040          | 46                                                    | 54          | -8          | 46                                               | 57          | -11          | 3          |
| <b>Mean:</b> | <b>47.6</b>                                           | <b>53.7</b> | <b>-6.4</b> | <b>47.3</b>                                      | <b>57.6</b> | <b>-10.1</b> | <b>3.7</b> |

## **APPENDIX G**

### **Average Ear Canal SNRs**

**Average Ear Canal SNR Subject Data for Right, Monaural Mode**

| Subject      | <u>Omni-Directional</u><br><u>Ear Canal SNR</u> |              |              | <u>Directional</u><br><u>Ear Canal SNR</u> |              |             | Benefit     |
|--------------|-------------------------------------------------|--------------|--------------|--------------------------------------------|--------------|-------------|-------------|
|              | MCL                                             | BNL          | SNR          | MCL                                        | BNL          | SNR         |             |
| 001          | 53.04                                           | 47.33        | 1.10         | 47.33                                      | 47.3         | 0.03        | -1.07       |
| 002          | 51.64                                           | 50.88        | -0.14        | 50.88                                      | 47.36        | 3.52        | 3.66        |
| 003          | 35.35                                           | 37.48        | -5.35        | 37.48                                      | 37.89        | -0.41       | 4.93        |
| 004          | 80.91                                           | 79.79        | -7.06        | 79.79                                      | 76.48        | 3.31        | 10.36       |
| 005          | 32.36                                           | 32.33        | 2.57         | 32.33                                      | 29.28        | 3.05        | 0.49        |
| 006          | 44.14                                           | 44.47        | -9.75        | 44.47                                      | 49.62        | -5.15       | 4.60        |
| 007          | 42.28                                           | 45.39        | -1.71        | 45.39                                      | 40.31        | 5.08        | 6.79        |
| 008          | 77.52                                           | 85.74        | -7.94        | 85.74                                      | 88.67        | -2.94       | 5.00        |
| 009          | 59.08                                           | 56.00        | -1.73        | 56.00                                      | 57.32        | -1.32       | 0.41        |
| 010          | 21.99                                           | 20.56        | -3.39        | 20.56                                      | 24.41        | -3.85       | -0.46       |
| 011          | 46.99                                           | 42.28        | 12.64        | 42.28                                      | 36.34        | 5.94        | -6.69       |
| 012          | 64.11                                           | 62.21        | 10.79        | 62.21                                      | 55.47        | 6.74        | -4.05       |
| 013          | 43.12                                           | 41.15        | 0.10         | 41.15                                      | 37.3         | 3.86        | 3.76        |
| 014          | 53.66                                           | 46.59        | 8.16         | 46.59                                      | 41.08        | 5.51        | -2.65       |
| 015          | 52.48                                           | 48.39        | 2.85         | 48.39                                      | 47.16        | 1.23        | -1.62       |
| 016          | 57.13                                           | 58.65        | 4.23         | 58.65                                      | 49.87        | 8.78        | 4.55        |
| 017          | 57.04                                           | 50.34        | -0.20        | 50.34                                      | 51.9         | -1.57       | -1.37       |
| 018          | 54.68                                           | 60.08        | -1.42        | 60.08                                      | 57.53        | 2.55        | 3.98        |
| 019          | 79.98                                           | 79.49        | -0.94        | 79.49                                      | 77.56        | 1.93        | 2.87        |
| 020          | 43.97                                           | 39.74        | -4.58        | 39.74                                      | 45.22        | -5.48       | -0.90       |
| 021          | 40.24                                           | 40.77        | 2.67         | 40.77                                      | 36.03        | 4.73        | 2.07        |
| 022          | 38.8                                            | 36.57        | 0.24         | 36.57                                      | 33.98        | 2.60        | 2.36        |
| 023          | 37.48                                           | 38.42        | -4.48        | 38.42                                      | 36.71        | 1.71        | 6.19        |
| 024          | 38.45                                           | 37.01        | -9.23        | 37.01                                      | 42.24        | -5.23       | 4.00        |
| 025          | 47.81                                           | 43.99        | -3.40        | 43.99                                      | 42.84        | 1.15        | 4.55        |
| 026          | 35.22                                           | 34.60        | -3.36        | 34.6                                       | 36.51        | -1.90       | 1.46        |
| 027          | 49.18                                           | 45.44        | 1.08         | 45.44                                      | 49.46        | -4.02       | -5.10       |
| 028          | 45.14                                           | 41.34        | -2.85        | 41.34                                      | 39.75        | 1.59        | 4.45        |
| 029          | 52.52                                           | 51.83        | 1.98         | 51.83                                      | 47.82        | 4.01        | 2.03        |
| 030          | 55.27                                           | 53.35        | -1.73        | 53.35                                      | 50.60        | 2.75        | 4.48        |
| 031          | 51.24                                           | 47.85        | -1.01        | 47.85                                      | 42.88        | 4.97        | 5.98        |
| 032          | 55.44                                           | 51.90        | -4.52        | 51.90                                      | 52.14        | -0.24       | 4.28        |
| 033          | 59.74                                           | 55.28        | 5.60         | 55.28                                      | 51.1         | 4.18        | -1.42       |
| 034          | 45.84                                           | 45.86        | -1.93        | 45.86                                      | 46.49        | -0.63       | 1.30        |
| 035          | 43.65                                           | 46.22        | -5.63        | 46.22                                      | 45.37        | 0.85        | 6.47        |
| 036          | 45.92                                           | 42.96        | 4.71         | 42.96                                      | 38.19        | 4.77        | 0.06        |
| 037          | 55.23                                           | 52.21        | -5.48        | 52.21                                      | 48.39        | 3.82        | 9.30        |
| 038          | 50.6                                            | 45.05        | -2.69        | 45.05                                      | 45.91        | -0.86       | 1.83        |
| 039          | 54.75                                           | 49.57        | -2.45        | 49.57                                      | 49.18        | 0.39        | 2.85        |
| 040          | 43.09                                           | 38.84        | 2.67         | 38.84                                      | 37.09        | 1.75        | -0.92       |
| <b>Mean:</b> | <b>49.93</b>                                    | <b>48.20</b> | <b>-0.79</b> | <b>48.20</b>                               | <b>46.77</b> | <b>1.43</b> | <b>2.22</b> |

**Average Ear Canal SNR Subject Data for Left, Monaural Mode**

| Subject      | <u>Omni-Directional</u><br><u>Ear Canal SNR</u> |              |              | <u>Directional</u><br><u>Ear Canal SNR</u> |              |             | Benefit      |
|--------------|-------------------------------------------------|--------------|--------------|--------------------------------------------|--------------|-------------|--------------|
|              | MCL                                             | BNL          | SNR          | MCL                                        | BNL          | SNR         |              |
| 001          | 53.07                                           | 53.84        | -0.78        | 46.38                                      | 47.21        | -0.83       | <b>-0.05</b> |
| 002          | 51.14                                           | 53.96        | -2.81        | 54.51                                      | 47.97        | 6.54        | <b>9.36</b>  |
| 003          | 39.17                                           | 44.08        | -4.92        | 38.31                                      | 42.06        | -3.74       | <b>1.17</b>  |
| 004          | 79.7                                            | 84.42        | -4.72        | 80.2                                       | 72.94        | 7.26        | <b>11.98</b> |
| 005          | 33.25                                           | 31.29        | 1.96         | 30.87                                      | 30.89        | -0.02       | <b>-1.98</b> |
| 006          | 46.48                                           | 50.27        | -3.8         | 41.49                                      | 41.49        | 0.00        | <b>3.80</b>  |
| 007          | 41.64                                           | 44.7         | -3.06        | 44.58                                      | 41.74        | 2.84        | <b>5.90</b>  |
| 008          | 66.19                                           | 79.11        | -12.92       | 72.75                                      | 66.97        | 5.78        | <b>18.70</b> |
| 009          | 52.85                                           | 62.69        | -9.84        | 52.83                                      | 60.94        | -8.11       | <b>1.73</b>  |
| 010          | 33.61                                           | 35.8         | -2.18        | 40.96                                      | 43.19        | -2.23       | <b>-0.05</b> |
| 011          | 48.54                                           | 39.66        | 8.88         | 47.28                                      | 38.89        | 8.38        | <b>-0.49</b> |
| 012          | 64.11                                           | 57.41        | 6.71         | 59.36                                      | 56.56        | 2.80        | <b>-3.91</b> |
| 013          | 41.71                                           | 43.01        | -1.30        | 43.51                                      | 38.54        | 4.97        | <b>6.27</b>  |
| 014          | 46.74                                           | 45.68        | 1.06         | 46.81                                      | 42.27        | 4.54        | <b>3.48</b>  |
| 015          | 51.6                                            | 43.61        | 7.99         | 50.1                                       | 42.48        | 7.62        | <b>-0.37</b> |
| 016          | 56.09                                           | 55.94        | 0.15         | 57.69                                      | 49.8         | 7.89        | <b>7.74</b>  |
| 017          | 56.78                                           | 64.8         | -8.02        | 53.22                                      | 59.04        | -5.82       | <b>2.19</b>  |
| 018          | 56.22                                           | 67.73        | -11.51       | 54.95                                      | 61.52        | -6.57       | <b>4.94</b>  |
| 019          | 73.79                                           | 77.26        | -3.47        | 76.1                                       | 74.31        | 1.79        | <b>5.26</b>  |
| 020          | 42.06                                           | 46.43        | -4.37        | 42.74                                      | 39.79        | 2.95        | <b>7.32</b>  |
| 021          | 53.13                                           | 58.39        | -5.27        | 49.04                                      | 47.01        | 2.04        | <b>7.30</b>  |
| 022          | 47.66                                           | 41.77        | 5.88         | 39.11                                      | 32.67        | 6.44        | <b>0.56</b>  |
| 023          | 44.61                                           | 48.57        | -3.96        | 40.96                                      | 45.27        | -4.31       | <b>-0.36</b> |
| 024          | 35.52                                           | 42.27        | -6.75        | 39.42                                      | 38.38        | 1.04        | <b>7.78</b>  |
| 025          | 54.23                                           | 58.96        | -4.74        | 44.34                                      | 47.22        | -2.88       | <b>1.86</b>  |
| 026          | 41.02                                           | 44.64        | -3.62        | 31.86                                      | 36.4         | -4.53       | <b>-0.91</b> |
| 027          | 51.84                                           | 54.61        | -2.77        | 46.02                                      | 46.02        | 0.01        | <b>2.77</b>  |
| 028          | 47.67                                           | 51.48        | -3.81        | 44.09                                      | 44.22        | -0.13       | <b>3.68</b>  |
| 029          | 46.70                                           | 51.68        | -4.97        | 51.16                                      | 47.18        | 3.98        | <b>8.95</b>  |
| 030          | 57.14                                           | 61.42        | -4.27        | 59.03                                      | 61.46        | -2.43       | <b>1.85</b>  |
| 031          | 49.41                                           | 50.79        | -1.38        | 46.5                                       | 47.09        | -0.59       | <b>0.80</b>  |
| 032          | 44.49                                           | 46.2         | -1.70        | 40.38                                      | 42.6         | -2.23       | <b>-0.52</b> |
| 033          | 55.22                                           | 65.14        | -9.92        | 58.73                                      | 51.45        | 7.28        | <b>17.19</b> |
| 034          | 50.77                                           | 53.84        | -3.07        | 52.94                                      | 49.28        | 3.66        | <b>6.73</b>  |
| 035          | 44.26                                           | 48.14        | -3.89        | 44.08                                      | 45.64        | -1.56       | <b>2.32</b>  |
| 036          | 38.00                                           | 43.86        | -5.86        | 39.52                                      | 43.41        | -3.89       | <b>1.97</b>  |
| 037          | 68.40                                           | 73.40        | -5.00        | 54.88                                      | 53.16        | 1.72        | <b>6.72</b>  |
| 038          | 52.23                                           | 60.26        | -8.03        | 54.44                                      | 53.28        | 1.16        | <b>9.19</b>  |
| 039          | 62.07                                           | 67.24        | -5.17        | 56.18                                      | 56.42        | -0.24       | <b>4.93</b>  |
| 040          | 42.45                                           | 40.97        | 1.48         | 47.05                                      | 50.82        | -3.77       | <b>-5.25</b> |
| <b>Mean:</b> | <b>50.54</b>                                    | <b>53.63</b> | <b>-3.09</b> | <b>49.36</b>                               | <b>48.44</b> | <b>0.92</b> | <b>4.01</b>  |

## Average Ear Canal SNR Subject Data for Binaural Mode

| Subject | <u>Omni-Directional</u><br><u>Ear Canal SNR</u> |       |        | <u>Directional</u><br><u>Ear Canal SNR</u> |       |       | Benefit |
|---------|-------------------------------------------------|-------|--------|--------------------------------------------|-------|-------|---------|
|         | MCL                                             | BNL   | SNR    | MCL                                        | BNL   | SNR   |         |
| 001     | 49.89                                           | 49.48 | 0.42   | 48.07                                      | 45.43 | 2.64  | 2.23    |
| 002     | 50.84                                           | 49.48 | -3.75  | 46.89                                      | 50.89 | -4.00 | -0.25   |
| 003     | 37.02                                           | 49.48 | -6.38  | 36.39                                      | 39.02 | -2.62 | 3.76    |
| 004     | 80.12                                           | 49.48 | -4.64  | 76.84                                      | 72.90 | 3.95  | 8.59    |
| 005     | 30.75                                           | 49.48 | -2.85  | 32.56                                      | 31.59 | 0.97  | 3.82    |
| 006     | 45.31                                           | 47.37 | -6.78  | 42.98                                      | 45.56 | 2.58  | 9.36    |
| 007     | 36.15                                           | 37.62 | -1.47  | 38.74                                      | 37.81 | 0.93  | 2.40    |
| 008     | 69.17                                           | 75.06 | -5.89  | 65.24                                      | 60.21 | 5.03  | 10.92   |
| 009     | 47.51                                           | 51.58 | -4.07  | 45.76                                      | 47.47 | -1.71 | 2.36    |
| 010     | 31.72                                           | 33.81 | -2.09  | 34.53                                      | 34.17 | 0.36  | 2.45    |
| 011     | 43.40                                           | 32.58 | 10.81  | 43.13                                      | 34.52 | 8.61  | -2.20   |
| 012     | 57.16                                           | 53.54 | 3.62   | 57.18                                      | 52.66 | 4.51  | 0.89    |
| 013     | 46.66                                           | 43.14 | 3.52   | 42.19                                      | 38.52 | 3.67  | 0.15    |
| 014     | 48.05                                           | 43.04 | 5.01   | 44.63                                      | 40.99 | 3.64  | -1.37   |
| 015     | 50.96                                           | 47.95 | 3.01   | 48.83                                      | 44.17 | 4.67  | 1.66    |
| 016     | 55.57                                           | 51.51 | 4.05   | 53.65                                      | 46.4  | 7.24  | 3.19    |
| 017     | 48.39                                           | 55.80 | -7.42  | 45.1                                       | 48.32 | -3.22 | 4.19    |
| 018     | 43.32                                           | 51.13 | -7.81  | 47.5                                       | 47.49 | 0.00  | 7.81    |
| 019     | 70.34                                           | 76.16 | -5.81  | 70.82                                      | 71.71 | -0.89 | 4.93    |
| 020     | 46.1                                            | 46.85 | -0.75  | 42.87                                      | 41.92 | 0.94  | 1.69    |
| 021     | 42.52                                           | 46.88 | -4.35  | 39.11                                      | 39.98 | -0.87 | 3.48    |
| 022     | 43.23                                           | 44.53 | -1.29  | 38.15                                      | 35.86 | 2.28  | 3.58    |
| 023     | 41.98                                           | 41.00 | 0.98   | 40.30                                      | 37.52 | 2.78  | 1.80    |
| 024     | 37.25                                           | 47.56 | -10.31 | 36.53                                      | 42.27 | -5.75 | 4.56    |
| 025     | 45.76                                           | 52.02 | -6.27  | 40.97                                      | 45.55 | -4.58 | 1.69    |
| 026     | 37.69                                           | 39.75 | -2.06  | 32.83                                      | 37.27 | -4.45 | -2.38   |
| 027     | 46.67                                           | 52.75 | -6.08  | 44.94                                      | 49.47 | -4.53 | 1.55    |
| 028     | 49.40                                           | 56.18 | -6.77  | 41.94                                      | 48.62 | -6.69 | 0.09    |
| 029     | 45.60                                           | 48.14 | -2.54  | 49.01                                      | 48.13 | 0.88  | 3.42    |
| 030     | 52.65                                           | 52.38 | 0.27   | 58.5                                       | 52.62 | 5.88  | 5.61    |
| 031     | 49.07                                           | 47.94 | 1.13   | 46.55                                      | 43.42 | 3.13  | 2.00    |
| 032     | 45.41                                           | 51.77 | -6.36  | 42.05                                      | 44.94 | -2.89 | 3.47    |
| 033     | 52.92                                           | 52.38 | 0.53   | 53.64                                      | 47.6  | 6.04  | 5.51    |
| 034     | 46.23                                           | 52.39 | -6.15  | 47.38                                      | 49.56 | -2.18 | 3.97    |
| 035     | 44.00                                           | 47.27 | -3.27  | 40.39                                      | 44.67 | -4.28 | -1.01   |
| 036     | 44.15                                           | 41.78 | 2.37   | 41.28                                      | 40.76 | 0.52  | -1.85   |
| 037     | 57.54                                           | 62.86 | -5.32  | 51.62                                      | 47.77 | 3.85  | 9.16    |
| 038     | 51.61                                           | 58.66 | -7.06  | 51.38                                      | 50.29 | 1.09  | 8.15    |
| 039     | 54.91                                           | 59.17 | -4.26  | 48.9                                       | 48.82 | 0.08  | 4.34    |
| 040     | 43.80                                           | 44.45 | -0.65  | 43.73                                      | 46.26 | -2.53 | -1.88   |
| Mean:   | 48.09                                           | 49.92 | -2.31  | 46.41                                      | 45.84 | 0.58  | 2.88    |

## **APPENDIX H**

### **Individual APHAB Scores**

**APHAB Subject Data for Ease of Communication Subtest**

| <b>Subject</b> | <b>Omni-Directional Subtest:<br/>Ease of Communication</b> | <b>Directional Subtest: Ease of<br/>Communication</b> | <b>Ease of Communication<br/>Benefit Score</b> |
|----------------|------------------------------------------------------------|-------------------------------------------------------|------------------------------------------------|
| 001            | 35.2                                                       | 57.8                                                  | -22.7                                          |
| 002            | 24.8                                                       | 29.0                                                  | -4.2                                           |
| 003            | 16.3                                                       | 33.3                                                  | -17                                            |
| 004            | 12.7                                                       | 16.8                                                  | -4.2                                           |
| 005            | 20.7                                                       | 14.2                                                  | 6.5                                            |
| 006            | 24.8                                                       | 1.0                                                   | 23.8                                           |
| 007            | 14.5                                                       | 14.5                                                  | 0.0                                            |
| 008            | 39.5                                                       | 39.5                                                  | 0.0                                            |
| 009            | 6.8                                                        | 6.8                                                   | 0.0                                            |
| 010            | 27.0                                                       | 26.8                                                  | 0.2                                            |
| 011            | 18.5                                                       | 19.8                                                  | -1.3                                           |
| 012            | 56.2                                                       | 56.2                                                  | 0.0                                            |
| 013            | 16.3                                                       | 31.2                                                  | -14.8                                          |
| 014            | 91.8                                                       | 91.8                                                  | 0.0                                            |
| 015            | 20.7                                                       | 22.7                                                  | -2                                             |
| 016            | 18.8                                                       | 18.8                                                  | 0.0                                            |
| 017            | 6.5                                                        | 6.5                                                   | 0.0                                            |
| 018            | 29.0                                                       | 29.0                                                  | 0.0                                            |
| 019            | 49.8                                                       | 46.0                                                  | 3.8                                            |
| 020            | 20.5                                                       | 20.5                                                  | 0.0                                            |
| 021            | 8.3                                                        | 8.3                                                   | 0.0                                            |
| 022            | 47.5                                                       | 35.0                                                  | 12.5                                           |
| 023            | 20.7                                                       | 24.8                                                  | -4.2                                           |
| 024            | 12.3                                                       | 20.8                                                  | -8.5                                           |
| 025            | 25.0                                                       | 25.0                                                  | 0.0                                            |
| 026            | 4.7                                                        | 4.7                                                   | 0.0                                            |
| 027            | 20.7                                                       | 20.7                                                  | 0.0                                            |
| 028            | 64.5                                                       | 31.2                                                  | 33.3                                           |
| 029            | 22.7                                                       | 18.5                                                  | 4.2                                            |
| 030            | 24.7                                                       | 24.7                                                  | 0.0                                            |
| 031            | 18.3                                                       | 24.7                                                  | -6.3                                           |
| 032            | 21.0                                                       | 10.5                                                  | 10.5                                           |
| 033            | 44.8                                                       | 44.8                                                  | 0.0                                            |
| 034            | 31.0                                                       | 31.0                                                  | 0.0                                            |
| 035            | 47.4                                                       | 45.0                                                  | 2.4                                            |
| 036            | 72.7                                                       | 83.0                                                  | -10.3                                          |
| 037            | 10.5                                                       | 19.0                                                  | -8.5                                           |
| 038            | 16.3                                                       | 16.3                                                  | 0.0                                            |
| 039            | 15.0                                                       | 12.7                                                  | 2.3                                            |
| 040            | 6.5                                                        | 6.5                                                   | 0.0                                            |
| <b>Mean:</b>   | <b>27.1</b>                                                | <b>27.2</b>                                           | <b>-0.1</b>                                    |

**APHAB Subject Data for Reverberation Subtest**

| <b>Subject</b> | <b>Omni-Directional Subtest:<br/>Reverberation</b> | <b>Directional Subtest:<br/>Reverberation</b> | <b>Reverberation<br/>Benefit Score</b> |
|----------------|----------------------------------------------------|-----------------------------------------------|----------------------------------------|
| 001            | 68.8                                               | 68.5                                          | 0.3                                    |
| 002            | 47.8                                               | 50.0                                          | -2.2                                   |
| 003            | 52.0                                               | 41.5                                          | 10.5                                   |
| 004            | 54.2                                               | 54.2                                          | 0.0                                    |
| 005            | 25.0                                               | 16.3                                          | 8.7                                    |
| 006            | 43.7                                               | 15.3                                          | 28.4                                   |
| 007            | 24.7                                               | 24.7                                          | 0.0                                    |
| 008            | 64.5                                               | 56.2                                          | 8.3                                    |
| 009            | 12.7                                               | 16.8                                          | -4.2                                   |
| 010            | 29.2                                               | 24.8                                          | 4.3                                    |
| 011            | 27.0                                               | 31.2                                          | -4.2                                   |
| 012            | 64.5                                               | 66.5                                          | -2.0                                   |
| 013            | 31.2                                               | 41.7                                          | -10.5                                  |
| 014            | 54.0                                               | 64.6                                          | -10.6                                  |
| 015            | 62.5                                               | 54.2                                          | 8.3                                    |
| 016            | 64.5                                               | 62.5                                          | 2.0                                    |
| 017            | 41.5                                               | 35.2                                          | 6.3                                    |
| 018            | 45.7                                               | 47.7                                          | -2.0                                   |
| 019            | 49.5                                               | 50.0                                          | -0.5                                   |
| 020            | 27.0                                               | 20.7                                          | 6.3                                    |
| 021            | 39.7                                               | 20.8                                          | 18.8                                   |
| 022            | 26.8                                               | 22.8                                          | 4.0                                    |
| 023            | 43.7                                               | 39.5                                          | 4.2                                    |
| 024            | 46.0                                               | 11.0                                          | 35                                     |
| 025            | 29.2                                               | 29.2                                          | 0.0                                    |
| 026            | 22.7                                               | 22.7                                          | 0.0                                    |
| 027            | 24.8                                               | 29.0                                          | -4.2                                   |
| 028            | 56.2                                               | 20.7                                          | 35.5                                   |
| 029            | 37.3                                               | 29.0                                          | 8.3                                    |
| 030            | 56.2                                               | 56.2                                          | 0.0                                    |
| 031            | 31.2                                               | 45.7                                          | -14.5                                  |
| 032            | 27.2                                               | 20.8                                          | 6.3                                    |
| 033            | 72.5                                               | 68.5                                          | 4.0                                    |
| 034            | 39.5                                               | 39.5                                          | 0.0                                    |
| 035            | 67.2                                               | 62.2                                          | 5.0                                    |
| 036            | 35.8                                               | 49.8                                          | -14.0                                  |
| 037            | 23.2                                               | 25.0                                          | -1.8                                   |
| 038            | 20.7                                               | 20.7                                          | 0.0                                    |
| 039            | 41.7                                               | 22.7                                          | 19.0                                   |
| 040            | 6.8                                                | 10.8                                          | -4.0                                   |
| <b>Mean:</b>   | <b>41.0</b>                                        | <b>37.2</b>                                   | <b>3.7</b>                             |

**APHAB Subject Data for Background Noise Subtest**

| <b>Subject</b> | <b>Omni-Directional Subtest:<br/>Background Noise</b> | <b>Directional Subtest:<br/>Background Noise</b> | <b>Background Noise<br/>Benefit Score</b> |
|----------------|-------------------------------------------------------|--------------------------------------------------|-------------------------------------------|
| 001            | 43.7                                                  | 58.2                                             | -14.5                                     |
| 002            | 60.3                                                  | 56.2                                             | 4.2                                       |
| 003            | 60.0                                                  | 56.2                                             | 3.8                                       |
| 004            | 56.0                                                  | 56.0                                             | 0.0                                       |
| 005            | 52.0                                                  | 22.7                                             | 29.3                                      |
| 006            | 66.5                                                  | 0.0                                              | 66.5                                      |
| 007            | 18.5                                                  | 18.5                                             | 0.0                                       |
| 008            | 62.3                                                  | 66.5                                             | -4.2                                      |
| 009            | 21.3                                                  | 21.3                                             | 0.0                                       |
| 010            | 58.3                                                  | 47.8                                             | 10.2                                      |
| 011            | 37.5                                                  | 30.0                                             | 7.5                                       |
| 012            | 72.7                                                  | 72.7                                             | 0.0                                       |
| 013            | 56.2                                                  | 20.7                                             | 35.5                                      |
| 014            | 72.5                                                  | 72.5                                             | 0.0                                       |
| 015            | 54.2                                                  | 54.2                                             | 0.0                                       |
| 016            | 62.3                                                  | 62.3                                             | 0.0                                       |
| 017            | 25.0                                                  | 23.2                                             | 1.8                                       |
| 018            | 43.7                                                  | 43.7                                             | 0.0                                       |
| 019            | 37.8                                                  | 31.5                                             | 6.3                                       |
| 020            | 43.7                                                  | 35.3                                             | 8.3                                       |
| 021            | 60.2                                                  | 24.8                                             | 35.3                                      |
| 022            | 33.3                                                  | 20.8                                             | 12.5                                      |
| 023            | 80.8                                                  | 68.7                                             | 12.2                                      |
| 024            | 40.7                                                  | 20.7                                             | 50.0                                      |
| 025            | 29.2                                                  | 29.2                                             | 0.0                                       |
| 026            | 54.3                                                  | 6.8                                              | 47.5                                      |
| 027            | 31.2                                                  | 26.8                                             | 4.3                                       |
| 028            | 72.7                                                  | 24.8                                             | 47.8                                      |
| 029            | 78.7                                                  | 66.5                                             | 12.2                                      |
| 030            | 43.7                                                  | 39.5                                             | 4.2                                       |
| 031            | 60.0                                                  | 50.0                                             | 10.0                                      |
| 032            | 52.0                                                  | 26.8                                             | 25.2                                      |
| 033            | 51.7                                                  | 49.8                                             | 1.8                                       |
| 034            | 35.3                                                  | 35.3                                             | 0.0                                       |
| 035            | 58.2                                                  | 43.7                                             | 14.5                                      |
| 036            | 46.0                                                  | 47.7                                             | -1.7                                      |
| 037            | 39.7                                                  | 37.7                                             | 2.0                                       |
| 038            | 47.8                                                  | 39.5                                             | 8.3                                       |
| 039            | 79.0                                                  | 45.8                                             | 33.2                                      |
| 040            | 6.5                                                   | 10.2                                             | -3.7                                      |
| <b>Mean:</b>   | <b>50.1</b>                                           | <b>39.1</b>                                      | <b>11.8</b>                               |

**APHAB Subject Data for Aversiveness to Sound Subtest**

| <b>Subject</b> | <b>Omni-Directional Subtest:<br/>Aversiveness to Sound</b> | <b>Directional Subtest:<br/>Aversiveness to Sound</b> | <b>Aversiveness to Sound<br/>Benefit Score</b> |
|----------------|------------------------------------------------------------|-------------------------------------------------------|------------------------------------------------|
| 001            | 37.2                                                       | 54.8                                                  | -17.6                                          |
| 002            | 14.5                                                       | 14.5                                                  | 0.0                                            |
| 003            | 39.5                                                       | 47.8                                                  | -8.3                                           |
| 004            | 48.2                                                       | 46.2                                                  | 2.0                                            |
| 005            | 15.0                                                       | 20.2                                                  | -5.2                                           |
| 006            | 18.7                                                       | 0.0                                                   | 18.7                                           |
| 007            | 35.2                                                       | 35.2                                                  | 0.0                                            |
| 008            | 33.3                                                       | 33.3                                                  | 0.0                                            |
| 009            | 2.8                                                        | 2.8                                                   | 0.0                                            |
| 010            | 52.2                                                       | 50.2                                                  | 2.0                                            |
| 011            | 2.8                                                        | 2.8                                                   | 0.0                                            |
| 012            | 16.3                                                       | 16.3                                                  | 0.0                                            |
| 013            | 76.8                                                       | 52.0                                                  | 24.8                                           |
| 014            | 41.7                                                       | 37.7                                                  | 4.0                                            |
| 015            | 33.3                                                       | 41.7                                                  | -8.3                                           |
| 016            | 37.3                                                       | 37.3                                                  | 0.0                                            |
| 017            | 23.2                                                       | 23.2                                                  | 0.0                                            |
| 018            | 25.0                                                       | 25.0                                                  | 0.0                                            |
| 019            | 31.3                                                       | 37.7                                                  | -6.3                                           |
| 020            | 70.3                                                       | 70.5                                                  | -0.2                                           |
| 021            | 42.0                                                       | 21.3                                                  | 20.7                                           |
| 022            | 39.7                                                       | 37.5                                                  | 2.2                                            |
| 023            | 45.7                                                       | 45.7                                                  | 0.0                                            |
| 024            | 22.8                                                       | 18.5                                                  | 4.3                                            |
| 025            | 54.2                                                       | 54.2                                                  | 0.0                                            |
| 026            | 27.2                                                       | 25.3                                                  | 1.8                                            |
| 027            | 56.3                                                       | 56.3                                                  | 0.0                                            |
| 028            | 74.7                                                       | 64.3                                                  | 10.3                                           |
| 029            | 62.3                                                       | 62.3                                                  | 0.0                                            |
| 030            | 8.3                                                        | 8.3                                                   | 0.0                                            |
| 031            | 58.3                                                       | 35.3                                                  | 23.0                                           |
| 032            | 95.0                                                       | 49.7                                                  | 45.3                                           |
| 033            | 47.7                                                       | 47.7                                                  | 0.0                                            |
| 034            | 72.0                                                       | 67.2                                                  | 4.8                                            |
| 035            | 68.5                                                       | 76.8                                                  | -8.3                                           |
| 036            | 88.8                                                       | 77.0                                                  | 11.8                                           |
| 037            | 27.3                                                       | 19.2                                                  | 8.2                                            |
| 038            | 49.8                                                       | 41.5                                                  | 8.3                                            |
| 039            | 93.0                                                       | 35.3                                                  | 57.7                                           |
| 040            | 16.7                                                       | 12.3                                                  | 4.3                                            |
| <b>Mean:</b>   | <b>42.6</b>                                                | <b>37.6</b>                                           | <b>5.0</b>                                     |

## Vita

Melinda “Mindy” Carol Freyaldenhoven was born in Memphis, Tennessee on May 24, 1979. She was raised in West Memphis, Arkansas and graduated from Immaculate Conception High School in 1997. Mindy graduated from the University of Central Arkansas in Conway, Arkansas with a Bachelor of Science degree in Speech Pathology in 2001. Mindy continued her education at the University of Tennessee in Knoxville, Tennessee, receiving her Master of Arts degree in Audiology in May 2003.