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The effects of asymmetric directional microphone fittings on acceptance of background noise

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THE EFFECTS OF ASYMMETRIC DIRECTIONAL MICROPHONE FITTINGS ON ACCEPTANCE OF BACKGROUND NOISE

by

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ABSTRACT

The present study investigated the effects of asymmetric directional microphone fittings (i.e., an omnidirectional microphone on one ear and a directional microphone on the other) on speech understanding in noise and acceptance of background noise in 15 full-time hearing aid users. Subjects were fitted binaurally with four directional microphone conditions (i.e., binaural omnidirectional, asymmetric right directional, asymmetric left directional and binaural directional microphones) using Siemens Intuis directional behind-the-ear hearing aids and comply earmolds. The results revealed that speech understanding in noise improved when using asymmetric directional microphones compared to binaural omnidirectional microphone fittings and were not significantly hindered compared to binaural directional microphone fittings. The results also revealed that listeners who wore asymmetric directional microphones were more likely to accept background noise (i.e., accept hearing aids) than listeners fitted with binaural omnidirectional microphones. Lastly, the results revealed that the ANLs were better for the binaural directional microphones when compared to the asymmetric directional microphones, maximizing listeners' willingness to wear hearing aids in the presence of noise.

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DEDICATION

For my wife, Sumin Jin, who has been devoting her life to others and continues to be an inspiration in my life.

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CHAPTER I

INTRODUCTION

Understanding speech in the presence of background noise is one of the most difficult challenges for hearing aid users. This is because listeners with sensorineural hearing loss require a better signal to noise ratio (SNR) than listeners with normal hearing to understand the same information. Research has demonstrated that hearing aids with binaural directional microphones or frequency modulation (FM) capabilities are the only viable options for improving speech understanding in noise. Directional microphones improve speech understanding by amplifying signals coming from the front, while reducing signals originating from the sides and the back (Cord, Surr, Walden, and Olsen, 2002). Likewise, FM systems improve speech understanding in noise by directly transmitting speech from the talker to the FM receiver, which is in the listener's ear. Furthermore, FM systems provide a better SNR by moving the microphone closer to the mouth of the speaker and attenuating the negative effects of distance, noise and reverberation (Lewis, 1994).

To improve speech understanding in noise abilities, directional microphones are available as an option for listeners with sensorineural hearing loss. Typically, program one is programmed as an omnidirectional microphone setting and program two is programmed as the directional microphone setting. However, some listeners are unwilling or unable to change their hearing aid program from an omnidirectional mode (the default setting) to the directional microphone mode. For these listeners, asymmetric directional microphones (defined as a bilateral hearing aid microphone fitting with an omnidirectional microphone mode in one ear and a directional mode on the other ear) may be a viable option. Additionally, many hearing aids today are automatic in nature and change hearing aid programs independently (Hornsby, 2006). In these cases, the audiologist cannot determine if the hearing aids change the programs together or if the patients function in an asymmetric directional microphone mode.

Furthermore, recent research has revealed that speech understanding in noise scores were not significantly degraded when listeners used asymmetric directional microphone settings compared to binaural directional microphones. More importantly, speech understanding in noise scores increased when listeners were fit with asymmetrical directional microphones compared to bilateral omnidirectional microphones (Cord, Walden, Surr, and Dittberner, 2007). It should be noted that speech understanding in noise scores assess the benefit hearing aids provide but do not predict hearing aid use (Nabelek, Tampas, and Burchfield, 2004). However, acceptance of background measured using the acceptance of noise level (ANL) procedure can predict hearing aid use.

ANL is a procedure which determines a listener's willingness to listen to speech in the presence of background noise. To obtain an ANL, subjects are asked to adjust running speech to their most comfortable listening level (MCL). Then, background noise is introduced and subjects are asked to adjust the level of background noise to the maximum background noise that they are willing to accept or "put up with" while listening to and following the words of a story (BNL). ANL is then obtained by subtracting the BNL from the MCL (i.e., MCL-BNL=ANL; Nabelek, Tucker, and Letowski, 1991). Research has shown that the ANL is not related to age, type of background noise distraction, gender, or hearing sensitivity (Nabelek et al., 1991). Research has also revealed that ANLs are reliable and consistent over time in listeners with both normal and impaired hearing (Nabelek, Freyaldenhoven, Tampas, Burchfield, and Muenchen, 2006). Furthermore, ANLs can predict hearing aid use with 85% accuracy (Nabelek et al., 2006).

Lastly, ANLs have been shown to be an alternative procedure for measuring the benefits of directional hearing instruments. Results of a study performed by Freyaldenhoven, Nabelek, Burchfield, and Thelin (2005) demonstrated that the effects of directional benefit could be measured using ANL, masked speech recognition thresholds (SRTs), and front to back ratio (FBRs). All three measures yielded a directional benefit of approximately 3 dB. The authors also stated that the ANL procedure is typically easier for the listener to complete and requires less time on the part of the examiner than either the masked SRT or FBR. These results suggest that ANL may be used as an alternative method to measure the benefits of directional hearing aids (Freyaldenhoven, Nabelek et al., 2005).

In summary, recent research suggests that the use of asymmetric directional microphones enhances speech understanding in noise abilities compared to bilateral omnidirecitonal microphone fittings and does not substantially degrade speech scores in contrast to binaural directional microphone fittings (Cord et al., 2007). The literature suggests that these types of fittings can be used on listeners who are unwilling or unable to change from the omnidirectional to the directional microphone mode. Likewise, it should also be noted that speech understanding in noise is a measure of directional benefit while ANL is a measure of listener's willingness to wear hearing aids (i.e., acceptance of hearing aids). However, ANLs have not been measured on listeners using asymmetric directional microphone hearing instruments. On one hand, it could be hypothesized that asymmetric directional microphone fittings will alter listener's acceptance of noise, thus increasing or decreasing their willingness to wear hearing aids. It could be also reasoned that asymmetric directional microphone fittings will not influence listener's acceptance of background noise, thus having no affect on willingness to wear hearing instruments. Therefore, the purpose of this study is to examine the effect of asymmetric directional microphone fittings on acceptance of background noise. The following specific research questions will be addressed:

1. Do asymmetric directional microphone fittings affect speech understanding in noise for listeners with hearing impairment?
2. Do asymmetric directional microphone fittings affect acceptance of background noise in listeners with hearing impairment?

CHAPTER II

REVIEW OF LITERATURE

Hearing Aid Microphones

Microphones in hearing instruments are either omnidirectional or directional in nature. Omnidirectional microphones amplify sounds equally from all directions. Directional microphones, on the other hand, amplify sounds arriving from the front, while suppressing sounds arriving from the sides and back of the listener. There are three types of directional microphones in hearing aids: traditional directional microphones, dual microphones or twin microphones, and d-mics (Ricketts and Mueller, 1999).

Directional Microphones

First, traditional directional microphones have two inlet ports (one in the front and one in the back) and operate on internal and external time delays. The internal time delay refers to the time delay that occurs due to an acoustic damper inside the hearing aid, and the external time delay refers to the time taken for a signal outside the hearing aid to get from one inlet port to the other. For example, when a sound arrives from behind the listener, it enters the rear microphone port first and is internally delayed by an acoustic damper. The sound then travels to the front microphone port after a short time delay; this time delay is directly related to the travel distance between the two ports. The sound entering the front microphone port is amplified by displacing one side of the diaphragm.

If the internal time delays and external time delays are equal, the sound displacing the diaphragm will cancel each other out, thus decreasing the sound coming from behind the listener.

Secondly, dual microphones or twin microphones contain two separate omnidirectional microphones with each with their own inlet port. Dual microphones operate on electronic delay (i.e., outputs/sounds coming from the rear are electronically delayed and subtracted from the output/sounds coming from front). Like the traditional directional microphone, if the output from the rear microphone is the exact same as the output from the front microphone, the output from the rear will be canceled, thus reducing sounds coming from behind the listener.

Lastly, d-mics contain one traditional directional microphone (two inlet ports) and one omnidirectional microphone (one inlet port), and both microphones work independent of the other. Therefore, either the omnidirectional or the directional microphone is activated to amplify sounds arriving from all directions (i.e., omnidirectional) or focusing on sounds coming primarily from the front (i.e., directional) (Ricketts and Muller, 1999).

All microphones in hearing instruments have a polar plot. A polar plot is a diagram of relative sensitivity of the microphone denoted in 360 degrees polar rotation. The polar plot for an omnidirectional microphone is in the shape of a circle and therefore equally sensitive to sounds arriving from all directions. Furthermore, directional microphones in hearing instruments will have one of four types of polar plots: cardioid, supercardioid, hypercardioid, or bidirectional (see Appendix A for polar plots). Each polar plot has one or two nulls, which are the point(s) at which the microphone is the least sensitive (Beck and Schum, 2005). First, the cardioid polar plot is sensitive to sounds coming from the front and sides and least sensitive to sounds arriving from the rear; the null is directly behind the listeners or at 180 degrees azimuth (see Appendix A; Luo, Yang, Pavlovic, and Nehorai, 2002). Second, the hypercardioid and supercardioid plots are sensitive to sounds coming from the front, while somewhat attenuating sounds from the sides and back. The nulls for the hypercardioid plot are at 110 and 250 degrees azimuth, and the nulls for the supercardioid polar plot are at 125 and 235 degrees azimuth (see Appendix A; Luo et al., 2002). Lastly, the bidirectional plot is sensitive to sounds coming from the front and rear and less sensitive to sounds arriving from the sides; the nulls for a bidirectional polar plot are at 90 and 270 degrees azimuth (Luo et al., 2002).

Furthermore, polar plots in hearing instruments can either be fixed or adaptive. Fixed polar plots do not change regardless of the location of the noise source. Conversely, the nulls of an adaptive polar plot automatically change based on the location of the noise source. Thus, the polar plot of the microphone potentially changes. For example, if the noise source changes from 180 degrees to 235 degrees, the polar plot will most likely change from a cardioid to a supercardioid pattern (Ricketts and Muller, 1999).

In summary, microphones in hearing aids are either omnidirectional or directional, and the polar plots in directional microphones can be fixed or adaptive. Therefore, when fitting two hearing instruments, various microphone fitting modes are available for audiologists. These include the fitting of two omnidirectional microphones, two directional microphones with fixed polar plots, two directional microphones with adaptive polar plots, or one omnidirectional microphone and either a fixed or adaptive directional microphone modes (called asymmetric or monofit microphone mode).

Asymmetric Directional Microphone Fittings

Recent studies regarding hearing aids with directional microphone have focused on the effect of fitting asymmetric directional microphone fittings on speech perception in noise scores. Many of these studies have demonstrated that speech perception in noise abilities and subjective quality ratings are not changed whether listeners are wearing asymmetric directional microphones or bilateral directional microphones. The following section summarizes the effects of asymmetric directional microphone fittings on speech understanding in noise scores and sound quality ratings.

First, Bentler, Egge, Tubbs, Dittberner, and Flamme (2004) investigated the effects of directivity indexes (i.e., a measure of directional benefit which compares sounds coming from the front to sounds originating from all other locations) on speech perception in noise and sound quality judgments. Nineteen adult hearing aid users (mean age = 67 years) with bilateral sensorineural hearing loss served as the participants. Each participant was fitted with bilateral Unitron Sound F/X in-the-ear (ITE) hearing aids. Speech perception in noise was assessed using the Hearing in Noise (HINT; Nilsson, Soli, and Sullivan, 1994) and Connected Speech Tests (CST; Cox, Alexander, and Gilmore, 1987). Additionally, participants rated eight areas of sound quality for three stimuli (speech in quiet, speech in background noise, and music). Five different microphone modes were examined for both the speech in noise testing and the sound quality judgments: omnidirectional, cardioid, hypercardioid, supercardioid, and monofit (an omnidirectional microphone fitted on the left ear and a directional microphone with a hypercardioid polar plot fitted on the right ear). All experimental measures were conducted in an anechoic chamber using an eight loudspeaker array.

Results of the speech perception in noise testing revealed poorer speech recognition ability for the ominidirectional microphone mode than for all other microphone modes. Furthermore, the results of the sound quality judgments showed no differences between any of the microphone modes. Most importantly, the results of the speech in noise testing and sound quality ratings exhibited no difference for the asymmetric mode compared to the other bilateral directional conditions. These results indicated that performance in noise was decreased when using an omnidirectional hearing instrument compared to asymmetric or directional hearing instruments; however, no differences were seen between speech understanding abilities when asymmetric and directional microphones were used. These results further indicated that subjective quality ratings were not dependent on microphone mode, at least when patients were tested in a diffuse field. Based on these results, Bentler et al. (2004) concluded utilization of one versus two directional microphones did not negatively affect patients' speech recognition in noise abilities or sound quality ratings.

Cord et al. (2007) continued the work of Bentler et al. (2004) by measuring the effects of asymmetrical hearing aid fittings in real life listening situations. Specifically, the investigators questioned (1) if asymmetric directional hearing aid fittings provide the same advantages that binaural directional fittings provide in noise and (2) whether asymmetric directional hearing aid fittings would be detrimental compared to binaural omnidirectional fittings in quiet listening situations. Twelve adults (mean age = 73 years) with bilateral symmetrical sensorineural hearing loss served as the participants. Each participant's own digitally programmable and manually switchable directional hearing instruments were used for the purposes of this study.

Furthermore, each listener participated in two experimental sessions. One session was conducted after the participants wore their hearing aids in the binaural omnidirectional mode, and the other was conducted after the participants wore their hearing aids in the asymmetric mode (defined as the wearing of one omnidirectional microphone fitting and one directional microphone fitting). Furthermore, the Hearing Aid Use Log (HAUL; Surr, Cord, Walden, and Olson, 2002), a daily journal used to record subjective measures of performance with hearing aids, was used to document listeners' ease of listening in daily listening situations with their hearing aids programmed to the binaural omnidirectional or asymmetric modes. Additionally, speech recognition in noise testing was conducted in the participant's second experimental session using the digitized Institute of Electrical and Electronic Engineers (IEEE 1969) speech materials for the following microphone modes: bilateral omindirectional, bilateral directional, asymmetric right (i.e., directional hearing instrument in the right ear and omnidirectional instrument in the left ear), and asymmetric left (i.e., directional hearing instrument in the left ear and omnidirectional instrument in the right ear). The IEEE sentences were presented from the front loudspeaker and the noise was presented from the sides and back.

Results of the speech recognition in noise testing revealed poorer speech recognition in noise scores for the bilateral omnidirectional mode than for the bilateral directional and asymmetrical modes; however, no differences were seen between speech in noise scores for the bilateral directional and asymmetrical microphone modes. The results further showed that the majority of listeners reported greater ease of listening for the asymmetric modes than for the bilateral omnidirectional mode when listening in noise. It should be noted that there was no significant difference for ease of listening between the binaural omnidirectional and asymmetric modes when listening in quiet. These results indicated that speech recognition in noise ability in the asymmetric directional mode improves relative to the bilateral omnidirectional mode and does not worsen relative to the bilateral directional mode. These results further indicated that an asymmetrical directional hearing aid fitting would not produce a negative effect on listeners' ease of listening in quiet and may improve their ease of listening ability in noise. Collectively, these results supported the use of asymmetric directional hearing aid fittings.

In a similar study, Hornsby and Ricketts (2007) hypothesized that noise source configuration and/or reverberation could introduce asymmetric deficits (i.e., deficits resulting from an asymmetric hearing aid fitting) in directional hearing aid fittings. Therefore, Hornsby and Ricketts (2007) investigated the effects of noise source configuration and reverberation on possible asymmetric deficits. Sixteen adults (mean age = 70 years) with bilateral mild to severe sensorineural hearing loss served as the participants. Using the participants' earmolds, the participants were fitted with bilateral Siemens Triano P behind-the-ear (BTE) hearing aids, which were adjusted to the following four microphone fitting modes: bilateral omnidirectional, asymmetric, and bilateral directional (Note: Two asymmetric modes were counterbalanced. That is, each subject was fitted with a directional microphone mode in the left ear and an omnidirectional microphone mode in the right ear or vice versa). The HINT (Nilsson et al., 1994) was used to evaluate the patients' speech understanding in noise in a moderately reverberant room. Each listener participated in three listening conditions: noise surround (i.e., speech from front and noise surrounds the listener), noise side (i.e., speech comes from the front and the noise source is located to the sides), noise and speech side (i.e., speech and noise are presented from the sides).

Results of this study revealed poorer HINT thresholds for the binaural omnidirectional mode than for the asymmetrical and binaural directional modes when the speech came from the front and the noise source surrounded the listener in a reverberant room. Additionally, HINT scores were poorer for the asymmetric directional mode than for the binaural directional mode when the speech was delivered from the front and the noise was presented from the sides or surrounding the listener. However, HINT scores in binaural omnidirectional mode were significantly better than binaural directional and asymmetric modes when the speech and noise sources are presented from the sides of the listener. Lastly, HINT scores were substantially poorer for the binaural directional mode than asymmetric directional microphone mode when the speech and noise came from the sides.

Results of this study indicated that the recommended type of microphone fitting is dependent on the noise source location. Specifically, maximum directional benefit was found with bilateral directional microphones when the speech source was located in front of the listener and noise surrounded or came from the sides of the listener. Additionally, bilateral omnidirectional microphones were of most use when the speech and noise were presented from the same side of the listener. Based on these results, the authors concluded that although asymmetric hearing aid fittings provide directional benefits in some listening situations, a symmetrical directional microphone maximally optimizes speech understanding in noise when speech comes from in front of the listener and the noise source is located to the side of or surrounds the listener.

Lastly, Mackenzie and Lutman (2005) examined the benefits of bilateral adaptive directional microphone fittings in various listening situations. Sixteen adult hearing aid users (mean age = 75 years) with bilateral moderate sensorineural hearing loss served as the participants. Using clinically recommended earmolds and tubes, each participant was fitted with bilateral Phonak Claro behind-the-ear (BTE) hearing aids. At the initial fit, omnidirectional and adaptive directional programs were set to each participant's hearing aids, and the participant was given a four-week acclimation period. Upon return, speech recognition in noise was measured in an anechoic chamber using the Bamford-Knowal-Bench sentences (BKB; Bamford, Knowal, and Bench, 1979). Four microphone modes were evaluated: bilateral omnidirectional, bilateral fixed directional, bilateral adaptive directional, and mixed microphone settings, including one hearing aid in the omindirectional mode and the other in the adaptive directional mode. Additionally, each participant was tested with speech coming from the front and noise coming from one of five of the following directions: from the front, from the rear, from both sides, and asymmetrically from both sides. That is, noise came from the right side (asymmetric right), or the left side (asymmetric left). Each listener's communication comfort was also measured with quality-rating scales, which included measures of overall listening comfort for speech and noise, speech and noise loudness, and speech clarity (Mackenzie and Lutman, 2005).

Results of the speech recognition in noise testing revealed no substantial differences between any of the microphone modes when noise was coming from the front. However, the results showed poorer speech recognition in noise scores for the bilateral omnidirectional mode than for all other directional settings (i.e., bilateral fixed, mixed, and bilateral adaptive) when noise was arriving from the sides and back.

Moreover, the bilateral adaptive mode was substantially better than all other microphone modes when noise was coming from the sides and back. The same trend was seen when the noise was presented asymmetrically. The only difference that existed was that speech recognition in noise scores for the bilateral fixed and mixed microphone modes was similar to the bilateral adaptive microphone mode. Results of this study also showed no substantial difference for clarity, comfort, or loudness of noise regardless of the microphone mode when noise arrived from the front. Additionally, speech was perceived as quieter for the bilateral adaptive and fixed microphone modes when noise was coming from the front. Furthermore, a significant advantage was seen for the bilateral fixed and adaptive relative to the mixed and omnidirectional microphone modes for clarity, comfort, and loudness of speech and noise when noise was arriving for all other directions. Based on these results, the authors concluded that the bilateral fixed and adaptive directional modes provided the greatest advantage for speech recognition in noise scores, with the adaptive mode providing the greatest benefit. These microphone modes also offered better sound quality, sound clarity, and listening comfort. Therefore, the authors recommended the use of bilateral adaptive directional microphones over bilateral fixed, mixed, or omnidirectional microphones in hearing aids.

In summary, recent research on the effects of asymmetric directional microphone fittings on speech perception in noise and subjective quality ratings has demonstrated the advantages of asymmetric directional microphone fittings over bilateral ominidirectional microphone fittings. Furthermore, asymmetric directional microphone fittings do not hinder speech in noise performance compared to bilateral directional microphone fittings for most listening situations. It should be noted, however, that the directional benefits associated with asymmetric microphone fittings may depend on noise source configuration.

Acceptable Noise Level

In 1991, Nabelek et al. introduced a procedure for measuring acceptance of background background noise while listening to speech. This procedure has become known as acceptable noise level (ANL) (then called tolerated signal to noise ratio [SNR]). To obtain an ANL, most comfortable listening levels (MCLs) and background noise levels (BNLs) are obtained. First, each participant adjusts running speech to their MCL. Then background noise is introduced, and the participants adjust the background noise to the most noise they are willing to "put up with" and still follow the words of the story (see Appendix B for ANL instructions). Finally, the ANL is calculated by subtracting the BNL from the MCL (MCL – BNL = ANL). For instance, if a listener's MCL is 70 dB HL, and his/her BNL is 50 dB HL, the ANL is 20 dB. ANLs are typically measured in the sound field with both the speech and background noise presented from 0 degree azimuth. Nabelek et al. (1991) measured ANLs in five groups of listeners (N = 15/group) to determine the effects of type of background noise distraction, age, hearing sensitivity, and self-perceived handicap on ANL. Group 1 included young normal hearing listeners (mean age = 21.73 years), and Group 2 (mean age = 70.87 years) was comprised of listeners with relatively good hearing. Groups 3 (mean age = 74 years) was made up of full-time hearing aid users (defined as those who wore hearing aids when needed); Group 4 (mean age = 74.80 years) consisted of part-time hearing aid users (defined as those who wore hearing aids occasionally), and Group 5 (mean age = 74.13 years) was composed of non-users of hearing aids (defined as those who had completely stopped using hearing aids). ANLs were measured using five types of background noise: multi-talker speech babble, speech-spectrum noise, traffic noise, light music such as that heard in a waiting room, and the sound of a pneumatic drill. Additionally, the hearing aid users completed the Hearing Handicap Inventory for the Elderly (HHIE: Ventry and Weinstein, 1982) to assess the effects of hearing impairment on everyday hearing aid use. All subjects were tested in a sound-treated booth using a monaural TDH-50 headphone. For the hearing impaired listeners, ANLs were obtained using a modified frequency response to simulate an appropriate hearing aid fitting.

Results of this study demonstrated that ANLs were not related to age, hearing sensitivity, or background noise distraction for most noises. The results also demonstrated that full-time hearing aid users exhibited significantly smaller ANLs than part-time and non-users of hearing aids for most background noise types. Part-time and non-users of hearing aids, however, could not be differentiated based on ANL. In other words, full-time users were willing to accept more background noise than part-time or non-users. Furthermore, the HHIE scores were not significantly different between the three groups of hearing aid users; however, the full-time hearing aid users perceived themselves as less handicapped when they wore hearing aids than when they did not wear hearing aids. These results indicated that ANL is not dependent on age, hearing sensitivity, or type of noise distraction. The results further indicated that ANL may be related to hearing aid use. Lastly, the fact that HHIE scores were not related to hearing aid use indicated that the reason part-time and non-users were not wearing hearing aids was not related to their perception of hearing loss. The HHIE may, however, be used as a measure of hearing aid benefit for some listeners.

ANL reliability and consistency over a three-month time period was investigated by Nabelek et al. (2004). ANL scores were also compared to speech perception in noise (SPIN; Bilger, Neutzel, Rabinowltz, and Rzeczkowski, 1984) scores in both aided and unaided listening conditions. Forty-one full-time hearing aid users and nine part-time users served as the participants. Aided (with hearing aids) and unaided (without hearing aids) ANLs and SPIN scores were measured in three experimental sessions: at initial hearing aid fitting, one-month post fitting, and three-months post fitting. The results revealed both unaided and aided ANLs and SPIN scores were highly reliable and consistent between the three test sessions. The results further revealed that unaided and aided ANLs were not significantly different; however, aided SPIN scores were significantly better than unaided SPIN scores. These results indicated that ANLs and SPIN scores were reliable, and acclimatization to hearing aids does not alter either ANLs or SPIN scores, at least over a three-month time period. These results further indicated that ANLs and SPIN scores measure two different reactions to background noise. Specifically, ANL may be used as a predictor of hearing aid use, while SPIN scores can be used to document hearing aid benefit (Nabelek et al., 2004).

Characteristics of Acceptable Noise Level

The following studies investigated the influence of gender, age, primary language of the speaker, preference for background sounds, and speech presentation level on ANL measurements. First, Rogers, Harkrider, Burchfield, and Nabelek (2003) studied the influence of gender on acceptance of background noise. Fifty young adults (25 male and 25 female) with normal hearing sensitivity served as the participants. The results demonstrated that males had significantly larger MCLs and BNLs than females; however, ANLs between the two groups were not significantly different. These results indicated that MCL and BNL may be dependent on gender; however, ANL is not dependant on the gender of the listener.

Secondly, Freyaldenhoven and Smiley (2006) examined if ANLs could be assessed in the pediatric population. Thirty-two children (16 eight year olds [mean age = 8.6 years] and 16 twelve year olds [mean age = 12.4 years]) with normal hearing sensitivity served as the participants. All participants were placed in a regular classroom for the entire school day, and there were an equal number of males and females in each age group. ANLs were obtained using the procedures of Nabelek et al. (1991) with one major exception: the instructions were altered to adjust for language differences in children (see Appendix B for ANL instructions). Six experimental ANL trials were completed within one session: three for speech spectrum noise and three for speech babble noise. Results of this study demonstrated that ANLs measured in children were not dependent on gender, age, or type of background noise distraction. The results further demonstrated that ANLs were reliable and normally distributed in children age 8 and 12 years. These results indicated that ANLs can be obtained reliably in children age 8 and 12 years; and ANLs are not dependent on age, gender, or type of noise distraction in the pediatric population. Based on these results, the authors concluded that ANLs should be measured on children with hearing impairment to determine if they could be used as a predictor of hearing aid acceptance or use in the pediatric population.

Thirdly, von Hapsburg and Bahng(2006) measured ANLs in listeners whose native language was Korean to determine (1) if ANLs could be measured in languages other than English, (2) if Korean ANLs compared to English ANLs, (3) the dependency of ANL on language in bilingual listeners (Korean-English), and (4) the relationship between speech perception in noise and ANLs in bilingual listeners. Thirty participants with normal hearing sensitivity participated in this study. The participants were divided into the following three groups: monolingual English listeners (N=10), moderately proficient bilingual Korean-English listeners (MPB, N=8; defined as self-reported moderate proficiency in English and passed the University of Tennessee SPEAK test with a score of 50 or higher), and low-proficiency bilingual Korean-English listeners (LPB, n=12; defined as self-reported minimal English language skills). The English ANL was determined in the conventional manner, and the Korean ANL was obtained using a prerecorded story about a ladybug read by a Korean male talker (primary stimulus) and the speech babble noise from the Korean SPIN (competing stimulus). The results revealed no difference in English ANLs among the three groups of listeners: monolingual English ANLs = 6.4 dB; MPB ANLs = 8.0 dB, and LPB ANLs = 6.8 dB. Additionally, Korean ANLs were similar to English ANLs for the same listeners. Lastly, the results revealed no relationship between speech perception in noise and ANLs in bilingual listeners. These results indicated that ANLs are unaffected by changes in language patterns (i.e., ANL is language independent), and ANLs may not be affected by language experience. However, it should be noted that the range of ANL in bilingual Korean-English listeners showed less variability (range = 4 to 14 dB) when compared to monolingual English listeners (range = -2 to 20 dB) (von Hapsburg and Bahng, 2006).

Fourthly, Freyaldenhoven, Smiley, Muenchen, and Konrad (2006) investigated the reliability of ANL in adults with normal hearing and the relationship between ANL and preference for background sound. Thirty adults (15 male and 15 female; mean age = 23 years) with normal hearing sensitivity served as the participants. Participants attended three experimental sessions scheduled approximately one week apart. During each session, three ANL measures were obtained for both speech babble and speech spectrum noise. Furthermore, a self-developed questionnaire evaluating personal preference for background sounds was completed during each session. The results revealed that ANLs were reliable within a session and consistent over a three-week time period. In addition, the results of the questionnaire showed that ANLs were not related to listeners' reported preference for background sounds, at least using the questionnaire in this study. Lastly, the results revealed that ANLs obtained with speech babble noise were 2 dB smaller than those obtained with speech spectrum noise. The results indicated that ANLs do not change over time, at least for a three–week time period. The results further indicated that ANLs cannot be determined by asking the listener questions about their preference for background sounds, at least with the questionnaire used in this study. Lastly, the authors concluded that ANLs obtained using different background noises should not be directly compared based on the 2 dB difference in ANLs for speech spectrum and speech babble noises (Freyaldenhoven, Smiley, Muenchen et al., 2006).

Fifthly, Franklin, Thelin, Nabelek, and Burchfield (2006) expanded the understanding of ANL to include measurements of ANL across a wide range of speech presentation levels. Twenty adults (mean age = 21.8 years) with normal hearing sensitivity served as the participants. ANLs were obtained at MCL and at five fixed presentation levels (20, 34, 48, 62, and 76 dB HL). Results demonstrated that ANL was dependant on speech presentation level. More specifically, for each 4 dB increase in speech presentation level, ANL increased by 1 dB. These results indicated that as speech presentation level increased, acceptance of noise also increased.

Freyaldenhoven, Plyler, Thelin, and Hedrick (2007) continued the work of Franklin et al. (2006) to determine if the effect of speech presentation level on acceptance of noise was related to the hearing sensitivity of the listener. Twenty-four individuals with normal hearing and 46 individuals with hearing impairment participated in this study. Because acceptance of noise is dependent on speech presentation level, participants with normal and impaired hearing were matched for conventional ANLs. ANLs were obtained conventionally (i.e., at MCL) and at eight fixed speech presentation levels: 40, 45, 50, 55, 60, 65, 70, and 75 dB HL. The effects of speech presentation level on acceptance of noise were analyzed using global ANL and ANL growth. To determine global ANL, ANLs for the fixed speech presentation levels were averaged for each participant. Furthermore, ANL growth was defined as the slope of the ANL function. The results revealed that global ANLs and ANL growth did not differ between listeners with normal and impaired hearing. The results further revealed that both global ANLs and ANL growth were related to conventional ANLs. Specifically, as conventional ANL increased, both global ANL and ANL growth also increased. These results indicated that the effects of speech presentation level on acceptance of noise were not dependent on hearing sensitivity (Freyaldenhoven et al., 2007).

Acceptable Noise Level and Hearing Aid Use

As previously stated, in 1991 Nabelek et al. introduced a procedure to quantify the amount of background noise an individual could accept while following the words of a story. Results of this study revealed that ANLs might be related to hearing aid use. In a similar study, Crowley and Nabelek (1996) hypothesized that hearing aid performance may be able to be predicted before the purchase of hearing aids. Therefore, Crowley and Nabelek (1996) analyzed 16 unaided variables in 46 participants with acquired, symmetrical, sensorineural hearing loss. All participants were first time binaural hearing aid users. The 16 unaided variables were age, gender, years of education, number of medications taken per day, percentage of employment time, pure-tone average (PTA), slope of the hearing loss, MCL, dynamic range, revised SPIN scores (Bilger et al., 1984), ANLs with multi-talker speech babble as the competing stimuli, ANLs with speech spectrum noise as the competing stimuli, Personal Adjustment and Communication Strategies scale scores from the Communication Profile for the Hearing impaired (CPHI, Demorest and Erdman, 1986), motivation for pursuing hearing aid use (self-motivation versus encouragement from others), and the difference between the national acoustic laboratories' (NAL; Byrne & Dillon, 1986) target gain and actual insertion gain.

The results revealed that the following unaided variables contributed to the prediction of the listeners' perceived hearing aid performance: age, slope of hearing loss, MCL, dynamic range of the listener, SPIN scores, ANLs with speech babble, Communication Strategies and Personal Adjustment scores from the CPHI, and the difference between NAL target gain and actual gain. These results further indicate that ANLs may be a predictor of success with hearing aids.

To further investigate if ANL could be used as a predictor of hearing aid use, Nabelek et al. (2006) investigated (1) the relationship between ANL, gender, age, PTA, and hours of daily hearing aid use; (2) the reliability of the self-developed pattern of hearing aid use questionnaire; and (3) the predictability of hearing aid use based on unaided ANL. The criteria for inclusion were binaural hearing aids obtained within the last three years and no known neurological or cognitive listener deficits. One hundred ninety-one participants were divided into three categories based on responses to the questionnaire: full-time (n=69), part-time (n=69), and non-users of hearing aids (n=53). Unaided ANLs and SPIN scores were obtained for all listeners while aided ANLs and

SPIN scores were obtained for 164 participants (Note: Twenty-seven participants could not complete the aided testing because they had returned their hearing aids). The results demonstrated that aided and unaided ANLs were not related to gender, age, or PTA. In addition, results revealed that only 3 of the 58 listeners who completed the questionnaire reported less hearing aid use after three months. Results further revealed that unaided ANLs were dependant on pattern of hearing aid use. Specifically, full-time hearing aid users had lower ANLs than part-time and non-users of hearing aids; however, part-time and non-users of hearing aids could not be differentiated. Therefore, the groups were redefined as successful (i.e., full-time) and unsuccessful (part-time and non-users) hearing aid users, and logistic regression analysis was calculated. The results revealed that the prediction of hearing aid use based on unaided ANL was 85% accurate. These results indicated that ANLs are not related to age, gender, or acquired hearing loss. The results further indicated that three months appears to be sufficient for a reliable determination of pattern of hearing aid use. Most importantly, these results indicated that ANL can be used as a predictor of success of hearing aid use with relatively precise accuracy.

Freyaldenhoven, Plyler, Thelin, and Muenchen (in press) recognized the following limitations to ANLs measured conventionally (i.e., at MCL): (1) the model assumes that hearing aid users only listen at one level in all daily listening situations; (2) both part-time and non-users of hearing aids cannot be differentiated based on conventional ANL; and (3) a 15% error rate occurs in the predictive model developed using conventional ANL. Therefore, Freyaldenhoven and colleagues (in press) investigated the effects of speech presentation level on acceptance of background noise in full-time, part-time, and non-users of hearing aids to determine if these effects could predict hearing aid use better than ANLs measured conventionally (i.e., ANLs at MCL).

Sixty-nine adults with hearing impairment were divided into three groups based on pattern of hearing aid use: full-time (N=25); part-time (N=21); and non-use of hearing aids (N=23). ANLs were obtained conventionally (at MCL; called conventional ANL) and at eight fixed speech presentation levels: 40, 45, 50, 55, 60, 65, 70, and 75 dB HL. While conventional ANLs were obtained for control purposes, the effect of speech presentation level on acceptance of background noise was analyzed using global ANLs (i.e., an average of ANLs for the fixed speech presentation levels) and ANL growth (i.e., the slope of ANL function) for each participant. The results revealed that global ANLs and ANL growth were significantly smaller for full-time hearing aid users than for either part-time or non-users of hearing aids; however, part-time and non-users of hearing aids could not be differentiated. Therefore, the groups were redefined as successful (i.e., full-time) and unsuccessful (part-time and non-users) hearing aid users, and logistic regression analysis was calculated.

The results revealed that global ANLs and ANL growth could be used to predict hearing aid use with 62% and 64% accuracy, respectively. The results further revealed that the overall accuracy for global ANL and ANL growth decreased in comparison to ANL measured conventionally (68%). These results indicated that the effects of speech presentation level on ANL differentiated the hearing aid user groups in the same manner as conventional ANLs. The authors, however, stated the effects of speech presentation level on ANL may be able to differentiate successful from unsuccessful hearing aid users with mid-range ANLs (Freyaldenhoven et al., in press).

Furthermore, post hoc analyses were conducted to determine if ANL measured at a single fixed speech presentation level could differentiate the three hearing aid groups better than ANLs measured conventionally (Freyaldenhoven et al., in press). The results revealed that ANLs obtained at 65, 70, and 75 dB HL differentiated the hearing aid groups in the same manner as conventional ANL. The results further revealed that accuracy of the prediction for the fixed speech presentation level slightly increased (74% at 65 dB, 70% at 70 dB, and 69% at 75 dB) in comparison to conventional ANLs (68%). These results indicated that hearing aid use may be able to be accurately predicted when ANLs are measured at fixed speech presentation levels.

Effects of Hearing Aids on Acceptable Noise Level

The following studies investigated the effects of binaural versus monaural amplification and the use of venting and low-frequency gain compensation on ANL. First, Freyaldenhoven, Plyler, Thelin, and Burchfield (2006) investigated the effect of monaural versus binaural amplification on speech understanding in noise and acceptance of background noise in 39 current binaural hearing aid users. Speech understanding in noise was measured using masked SRTs, and acceptance of background noise was measured using the conventional ANL procedure.

The results revealed a significant improvement in masked SRTs with binaural versus monaural amplification; however, there was no improvement in ANL with binaural versus monaural amplification. These results indicated that speech understanding in noise improves with binaural amplification; however, ANL is unaffected by monaural versus binaural amplification. Based on these results, the authors concluded that listeners should be fitted with binaural hearing aids to improve speech understanding in noise while ANL (i.e., hearing aid use) remains unaffected.

Furthermore, it should be noted that individual data analysis revealed some listeners' best monaural score was better than their binaural score, indicating that some listeners may be more willing to use amplification if fitted monaurally instead of binaurally. Individual data analysis further revealed that some listeners exhibited interaural ANL differences, indicating that acceptance of hearing aids and noise may be dependent on the ear fitted if only one hearing aid is fitted.

Second, Freyaldenhoven, Plyler, Thelin, Nabelek, and Burchfield (2006) investigated the effects of venting and low-frequency gain compensation on speech understanding in noise and acceptance of background noise in listeners wearing hearing instruments with directional microphones. A secondary goal of this study was to determine if a relationship existed between low-frequency gain compensation and/or venting and degree of low-frequency hearing loss of the listener. Nineteen binaural hearing aid users with symmetrical sensorineural hearing loss were included in this study. The listeners were separated into 2 groups: one group included listeners with no low-frequency hearing loss, and the other included listeners with a low-frequency hearing loss. Each listener was fitted with two behind-the-ear (BTE) Starkey Axent II hearing aids. The HINT was used to test speech understanding in noise, and the conventional ANL procedure was used to evaluate acceptance of noise.

Results of the study revealed that the group with no low-frequency hearing loss performed significantly better than the group with low-frequency hearing loss on the speech understanding in noise test (i.e., HINT); however, speech understanding in noise was unaffected by venting or low-frequency gain compensation for either group. Results of the study also revealed that ANL was not affected by venting, low-frequency gain compensation, or hearing sensitivity. These results indicated that listeners with better low-frequency hearing can be expected to understand speech in the presence of background noise better than those with poorer low-frequency hearing and that this is independent of vent size or amount of gain compensation. These results also indicated that a listener's acceptance of background noise, thus their acceptance of hearing aids is unaffected by venting or low-frequency gain compensation. For clinical purposes, it is important to note that clinicians can alter both vent size and low frequency gain compensation without decreasing speech intelligibility or decreasing the likelihood of the patient's acceptance of the hearing aid.

Medication of Acceptable Noise Level

The following studies aimed to determine whether ANL is mediated peripherally or centrally. First, Harkrider and Smith (2005) examined the role of the auditory efferent system on ANL. Monotic ANLs (i.e., ANLs obtained with speech and noise presented ipsilaterally) and dichotic ANLs (i.e., ANLs obtained with speech and noise presented to both ears simultaneously) were measured in 31 adults with normal hearing. These were compared to monotic phoneme recognition in noise scores (PRN, defined as the recognition of phonetically balanced, monosyllabic words presented in the presence of an ipsilaterally competing stimulus), ipsilateral and contralateral acoustic reflex thresholds (ARTs), and contralateral suppression of transient evoked otoacoustic emission (CSTEOAE).

The results revealed a direct relationship between monotic and dichotic ANLs. Additionally, the results revealed that neither monotic nor dichotic ANLs were related to

PRN scores, ARTs, or CSTEOAEs. Because the level of efferent activity in the contralateral AR arc is correlated with the level of efferent activity in the medial olivary cochlear bundle (MOCB) pathway, these results indicated that non-peripheral factors, at or beyond the superior olivary complex, mediate ANL. The results also indicate that ARTs or CSTEOAEs may not be helpful additions to clinical routines when attempting to determine hearing aid success.

Next, Harkrider and Tampas (2006) measured physiological responses including click-evoked otoacoustic emissions (CEOAEs), auditory brainstem responses (ABRs) and middle latency responses (MLRs) in 13 females with normal hearing sensitivity. The females were divided into two groups based on ANL score: low ANLs (N=6; ANLs $\leq$ 6 dB), and high ANLs (N=7; ANLs $\geq$ 16 dB). Results of this study revealed no differences between the groups for CEOAEs or the amplitudes and latencies of waves I or III of the ABR; however, differences did exist for the amplitudes and latencies of wave V of the ABR and Na-Pa of the MLR. Specifically, listeners with low ANLs had smaller wave V amplitudes and Na-Pa peaks. These results further support the hypothesis that ANL is mediated in the more central regions of the auditory nervous system. In addition, these results indicate that the females with low ANLs may have suppressed afferent transmission or stronger efferent mechanism than females with high ANLs. Conversely, females with high ANLs may have enhanced afferent transmission or weaker efferent mechanisms than females with low ANLs.

Tampas and Harkrider (2006) continued to investigate the effects of auditory evoked potentials on ANLs. In addition to ABRs and MLRs, long latency responses (LLRs) were measured in 21 young females with normal hearing. Again, the listeners were separated into two groups depending on if they had low (N = 11) or high (N = 10)

ANLs. Additionally, ANLs were obtained at 35, MCL, 70 dB HL. Like Harkrider and Tampas (2006), the results revealed no differences between the two groups for the early ABR waves; however, differences emerged for the later waves of the ABR as well as the MLR and LLR peaks. The results further revealed that females with low ANLs demonstrated a slower rate of growth in ANL (ANL growth = .15 dB/dB) with increasing speech presentation level than listeners with high ANLs (ANL growth = .44 dB/dB). The results indicated that ANL is mediated in the central auditory nervous system and listeners with high ANLs process background noise differently than those with low ANLs. The authors contributed these differences to differences in responsiveness of central regions of the auditory system, which they explained may account for large inter-subject variability in listeners' willingness to accept background noise.

Ways to Improve an Acceptable Noise Level

Results from the following studies provide some insight into factors which may improve an individual's ANL using either hearing aid technology or pharmacology. First, Freyaldenhoven, Nabelek et al. (2005) investigated the suitability of the ANL procedure for assessing the benefit of directional microphones in hearing aids. Forty experienced hearing aid users participated in this study. ANL measurements, masked SRTs, and FBRs were measured utilizing both omnidirectional and directional microphones (Note: Masked SRTs were obtained solely for reliability purposes). Results from this study revealed that the directional benefit measured using the ANL, masked SRT, and FBR procedures were similar. More specifically, all three measures yielded a directional benefit of approximately 3 dB. The investigators also stated that the ANL procedure is typically easier for the listener to complete and requires less time for the examiner than either the masked SRT or FBR. This indicates that ANL may be an alternative method for measuring directional benefit.

In a similar study, Mueller, Weber, and Hornsby (2006) investigated the effects of digital noise reduction (DNR) on ANL and aimed to determine if the patient's degree of hearing loss, insertion gain, speech intelligibility in noise, and unaided and aided MCLs could be used to predict ANLs. Twenty-two binaural hearing aid users, each with a symmetrical mild to moderate sensorineural hearing loss, were included in this study. All participants were tested using bilateral Siemens ACURIS Model S BTE hearing aids. Moreover, if the participants did not have their own earmolds, foam comply tips were provided to the participants. ANLs were obtained using the speech and noise portions from the HINT.

Results revealed that ANLs obtained with DNR on were smaller than ANLs obtained with DNR off. Results further revealed that ANL was not related to speech understanding in noise abilities, patient's degree of hearing loss, or insertion gain. These results indicated that DNR can significantly improve acceptance of background noise, at least when measured using the HINT as the primary stimulus.

Furthermore, to determine if ANLs could be improved using pharmacological intervention, Freyaldenhoven, Thelin, Plyler, Nabelek, and Burchfield (2005) examined the effect of stimulant medication on ANL in individuals with attention deficit/hyperactivity disorder (ADD/ADHD) and measured the influence of speech presentation level on ANL in persons with ADD/ADHD. Fifteen young females who were on stimulant medication for treatment of ADD/ADHD and had normal hearing sensitivity served as the participants for this study. Each listener participated in two sessions. One session was conducted while the listeners were taking medication for treatment of ADD/ADHD, and the other session was performed after the participants had been off the medication for at least 12 hours. The ANLs were measured at 20 dB HL, MCL, and 76 dB HL. ANLs measured at MCLs were obtained in the conventional manner. For the fixed speech presentation levels (i.e., 20 and 76 dB HL), the running speech remained constant while the listener adjusted the background noise to their BNL. Results of the Freyaldenhoven, Thelin et al. (2005) study revealed that as speech presentation level increased, ANL also increased. The results further revealed that ANLs improved while the participants were on stimulant medication for the treatment of ADD/ ADHD in comparison to the results with no medication. These results indicated that listeners with ADD/ADHD can accept more background noise when taking stimulant medication for the treatment of ADD/ADHD and provided the first evidence that pharmacological intervention could manipulate ANLs.

CHAPTER III

METHODS

Participants

Fifteen adults with bilateral sensorineural hearing loss were recruited from the Louisiana Tech Speech and Hearing Center to participate in this study. Upon arrival, each subject was required to sign an informed consent in accordance with the institutional review board procedures at Louisiana Tech University (see Appendix C for informed consent). The criteria for subject inclusion were as follows: (1) symmetrical sensorineural hearing impairment (i.e., no more than a 15 dB HL difference in pure-tone thresholds at any octave frequency 250 Hz through 8000 Hz between ears; ANSI S3.6-1996; (2) current full-time and binaural hearing aid users who have worn hearing aids for at least three months and, (3) native English speakers with no known neurological, cognitive, or learning deficits as reported by the subjects.

It should be noted that full-time hearing aid users were defined as listeners who wore hearing aids whenever they need them, independent of number of hours per day. All qualification and experimental testing was conducted in a sound-treated examination room (IAC-30, 9'3'' by 9'7'') in Woodard Hall (Louisiana Tech University campus) with ambient noise levels appropriate for testing unoccluded ears (ANSI S3.1-1991). Figure 1 shows the mean pure tone thresholds for the right and left ears of the participants.

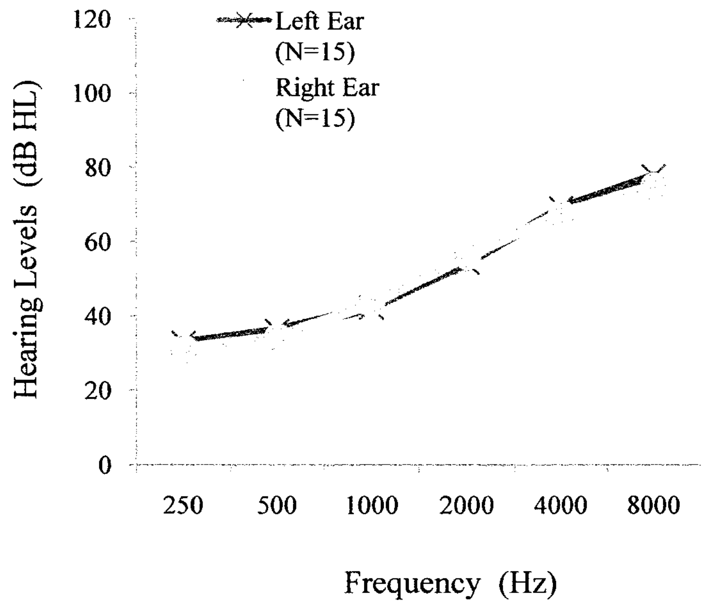

Figure 1 Mean pure tone thresholds for the right and left ears of all participants.

Hearing Instruments

Two digital BTE hearing instruments with twin microphones (fixed hypercardioid polar plot) and multiple memory capabilities (Siemens Intuis Dir) were utilized in the study. The same two hearing instruments were used for each participant and were fit binaurally using comply earmolds. The audiometric data of each participant was used to program each hearing instrument using the National Acoustic Laboratories (NAL-R) fitting strategy (Byrne and Dillon, 1986) (Note: Linear processing was utilized to prevent differential effects caused by compression [Ricketts, 2000]). Two memories of the digital hearing instruments were programmed for each participant (Siemens First Fit). All fitting parameters of program 1 were identical to all fitting parameters of program 2; however, a fixed ominidirectional microphone was used in program 1 and a fixed directional microphone was utilized in program 2 (see Appendix D for hearing aid fitting procedures). Moreover, all other fitting parameters were held constant across the two memories. The noise reduction and feedback suppression features were deactivated for the entire experiment, and the volume control setting was unchanged during the entire test sessions.

Test Box Measures

The hearing aids were placed in the Audioscan Verifit test box with the hearing aid's front microphone port facing the front loudspeaker and the rear microphone port facing the rear loudspeaker. It should be noted that this is the recommended protocol for testing directivity for this system. Test box measures were then obtained with the hearing aid in both the omnidirectional and directional modes. For both modes, the response received from the front loudspeaker was subtracted from the response obtained from the back loudspeaker. This was performed to quantify the directional effects for the two different microphone modes: omnidirectional and directional. Pink noise was presented at 65 dB SPL from 250 Hz to 8000 Hz in 1/3 octave steps (see Appendix E for test box measurement procedures). The following measures were obtained: omnidirectional front loudspeaker, omnidirectional back loudspeaker, directional front loudspeaker, and directional back loudspeaker. Therefore, a total of 8 measurement curves were obtained and entered into a Microsoft Excel program in order to complete subsequent data analysis

Speech Understanding in Noise

The HINT (Nilsson et al., 1994) served as the stimuli for evaluating speech understanding in noise. The HINT is a prerecorded test, which is composed of 25 lists of 10 English sentences. Conventionally, the background noise level is presented at a fixed level of 65 dB SPL, and the presentation level of the HINT sentences depends on the subject's accurate performance on each sentence. Specifically, for the first four sentences, the speech presentation level was increased by 4 dB for wrong answers and decreased by 4 dB for correct answers. For the sentences from five to ten, the speech presentation level was increased by 2 dB for wrong answers and decreased by 2 dB for correct answers (see Appendix F for HINT instructions). The speech reception threshold was recorded for each sentence. Then, the HINT protocol utilized in the present study reflected a slight modification of the original HINT protocol in that noise levels were varied and speech levels were fixed at the patient's MCL. This protocol variation ensured that speech levels were consistent between the HINT and the ANL stimuli.

Speech understanding in noise was assessed for the following microphone modes: binaural omnidirectional fitting (called omnidirectional mode), asymmetric directional microphone fitting with an omnidirectional microphone on the left ear and a directional microphone on the right ear (called right asymmetric mode), an asymmetric directional microphone fitting with an omnidirectional microphone on the right ear and a directional microphone on the left ear (called left asymmetric mode), and a binaural directional microphone (called directional mode). Participants were seated approximately 2 meters from each loudspeaker (0° and 180° azimuth) in the center of a sound-treated room. The sentences were presented through an ear-level loudspeaker located at 0° azimuth while the HINT background noise was presented through an ear-level loudspeaker located at 180° azimuth. Two HINT trials were conducted for each microphone mode, and an average of the two trials served as the mean HINT score for that participant in the given condition. Therefore, a total of 8 HINT measurements were obtained for each subject.

Acceptance of Background Noise

Acceptance of background noise was assessed using the acceptable noise level (ANL) procedure. A recording of male running speech (Arizona Travelogue, Cosmos, Inc.) and multitalker speech babble (Revised SPIN; Bilger et al., 1984) served as the stimuli. To obtain an ANL, most comfortable listening levels (MCLs) and background noise levels (BNLs) were obtained using the methods developed by Nabelek et al. (2006). First, each participant adjusted running speech to their MCL (see Appendix B for MCL instructions). Then background noise was introduced, and the participant was asked to adjust the background noise to the most they were willing to "put up with" while listening to and following the words of a story (called BNL; see Appendix B for BNL instructions). The initial presentation for both speech and noise stimulus was 30 dB HL. The ANLs were obtained by subtracting the BNL from the MCL. For example, if a participant's MCL was 60 dB HL and their BNL was 40 dB HL, the ANL was 20 dB [MCL (60) - BNL (40) = 20 dB].

Acceptance of background noise was assessed for each microphone mode (binaural omnidirectional mode, right asymmetric mode, left asymmetric mode, binaural directional mode). Again, participants were seated about 2 meters from each loudspeaker (0° and 180° azimuth) in the sound-treated room. The male running speech was presented from 0° azimuth while the multitalker speech babble was presented from 180° azimuth. Two ANL trials were conducted for each microphone mode, and an average of the two trials served as the mean ANL for that participant in the given condition. Therefore, a total of 8 ANL measurements were obtained for each participant.

All speech stimuli and background noise were produced by a compact disc player (Tascam CD-160, serial # 0231289) and routed through a clinical audiometer (GSI-61; serial # AA063067) to two ear-level loudspeakers located at 0° and 180° azimuth, respectively. The output levels of the speech stimuli and background noise were calibrated at the vertex of the listener and were checked periodically throughout the experiment. Prior to data collection, an experimental schedule was generated for each participant listing a randomized assignment for each microphone mode. ANL and HINT procedures were then counterbalanced within each microphone mode (Note: HINT sentences were assigned at random).

CHAPTER IV

RESULTS

Test Box Measures

To ensure proper hearing aid function, test box measures were completed using each patient's audiometric data and hearing aid settings. The directionality of each microphone condition (i.e., omnidirectional and directional) was measured using the Audioscan Verifit. Measurements were taken using pink noise delivered at 65 dB SPL for each microphone condition. A total of eight output curves were recorded for each subject: omnidirectional response from the front speaker, omnidirectional response from the back speaker, directional response from the front speaker, and directional response from the back speaker for the right and left ears. Figure 2 shows the frequency response curves when the hearing aid was set to the omnidirectional and directional modes and the noise was arriving from the front and back speakers.

The average response curves of the binaural omnidirectional front and back conditions mimic each other. These results verify that when the omnidrectional microphone was utilized, the front and back microphones were equally sensitive, thus functioning appropriately. Conversely, the response curve from the directional microphone front condition was more sensitive than that of directional microphone back condition, indicating that the directional microphone was in fact suppressing noise arriving from the back while maintaining sensitivity to the front. Shown differently, the

the response from the back microphone was subtracted from the response from the front microphone for both microphone conditions (i.e., omnidirectional and directional). Figures 3 (right ears) and 4 (left ears) indicated that the directional microphone settings generated a 3 to 7 dB intensity difference across the test frequencies for both ears compared to the omnidirectional microphone settings, indicating that the directional microphones were functioning properly.

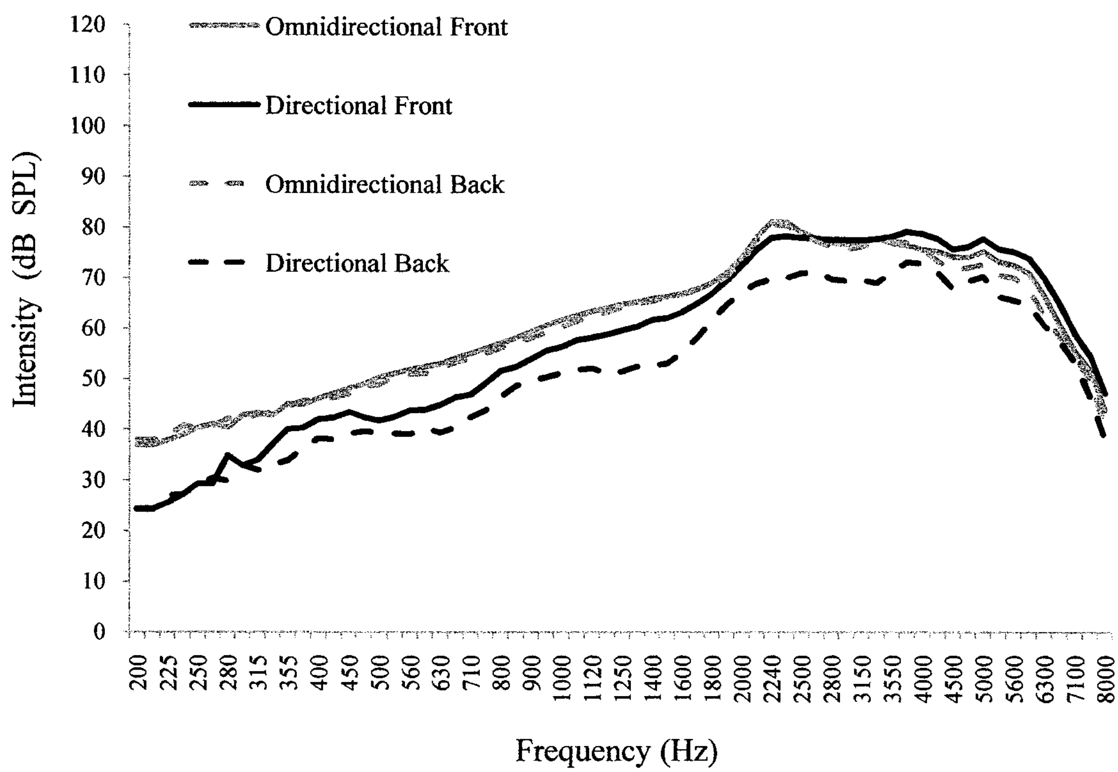

Figure 2 Average SPLs as a function of frequency for the omnidirectional and directional settings when measured from the front and back loudspeakers of the Verifit for 30 ears.

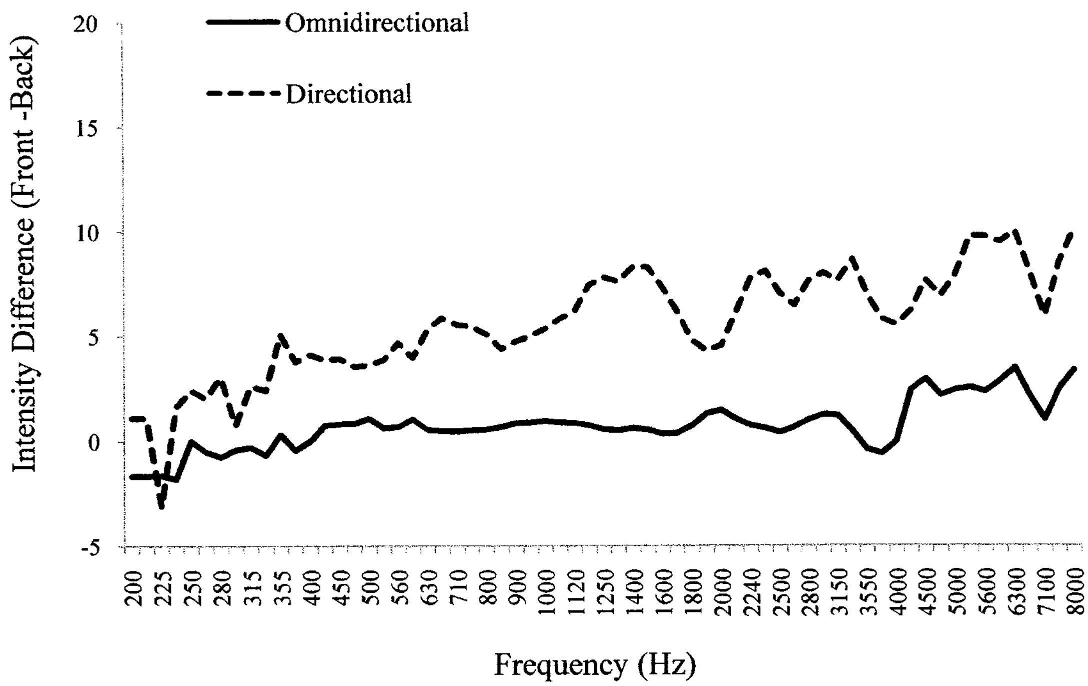

Figure 3 SPL difference between the front and back response for the omnidirectional and directional microphone conditions for all right ears. Note: Difference was calculated by subtracting front response from the back response.

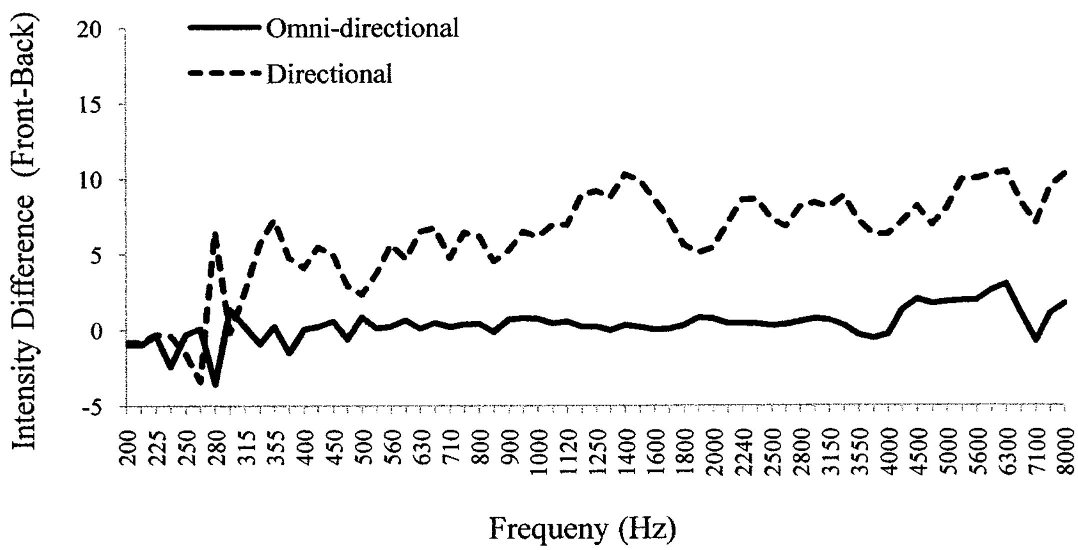

Figure 4 SPL difference between the front and back response for the omnidirectional and directional microphone conditions for all left ears.

Speech Understanding in Noise

One purpose of the present study was to investigate the effect of asymmetric directional microphone fittings on speech understanding in noise. HINT scores were measured for each microphone condition (i.e., binaural omindirectional, right asymmetric directional, left asymmetric directional, and binaural directional) at the listener's MCL, which was obtained using the ANL procedure. The HINT was replicate for each condition, and mean HINT scores were determined for each participant. Mean HINT scores across participants and condition are shown in Figure 5.

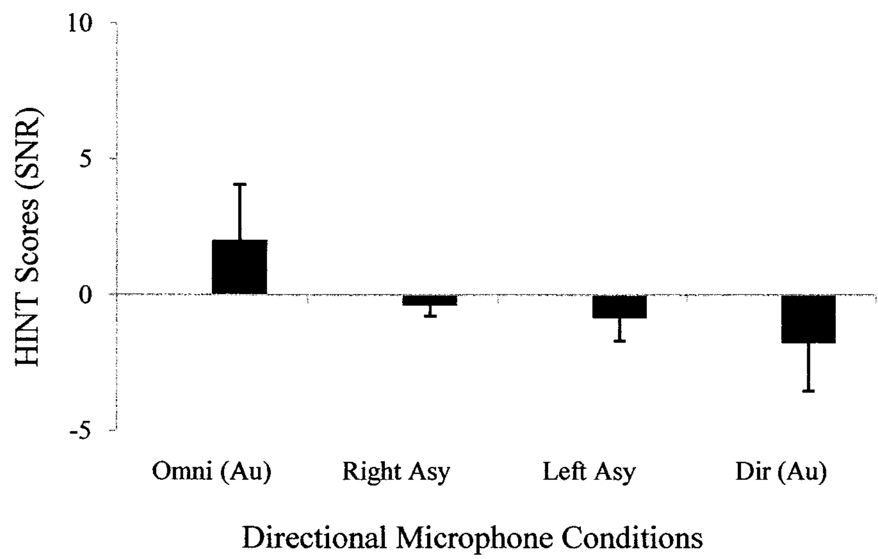

Figure 5 Mean HINT scores and standard deviations as a function of the four microphone conditions for the right and left ears.

A one-way repeated measure analysis of variance (ANOVA) was conducted to evaluate the effects of microphone condition on speech understanding in noise. The dependent variable was HINT score. The within subjects factor was microphone condition with four levels (binaural omnidirectional, asymmetric right, asymmetric left, and binaural directional). The analysis revealed a significant main effect for microphone condition ($F[3, 42] = 12.002$, $p < 0.001$). Furthermore, post hoc analyses were conducted using pariwse comparisons; a Bonferroni adjustment was applied for multiple comparisons.

Pairwise comparison results revealed HINT scores were significantly better for both the binaural directional and asymmetric directional microphone conditions as to the binaural omnidirectional condition. However, no significant differences were seen between the HINT scores for the binaural directional conditions or the two asymmetric directional conditions (see Table 1).

Table 1

Post hoc analysis comparing mean HINT scores for each microphone condition.

Microphone Condition	HINT scores
Binaural Omnidirectional	$2.03_{A, B, C}$
Asymmetric Directional (R)	-0.38_{A}
Asymmetric Directional (L)	-0.85_{B}
Binaural Directional	-1.77_{C}

Note: Any two means in the same column with the same subscript are significantly different.

These results indicated a significant improvement in speech in noise scores when listeners were fit with either asymmetric directional or binaural directional microphones compared to binaural omnidirectional microphones. Furthermore, no differences were found between in speech scores when listeners were fit with either asymmetric directional microphones (right or left) or bilateral directional microphones, indicating that speech understanding in noise scores are not hindered when using asymmetric directional microphone fittings compared to bilateral directional microphone fittings.

Acceptance of Background Noise

Another purpose of the present study was to determine if asymmetric directional microphone fittings affected acceptance of background noise. ANLs were obtained twice for each microphone condition (i.e., binaural omindirectional, asymmetric right asymmetric directional, left asymmetric directional, and binaural directional), and a mean ANL was determined for each participant. Mean ANL scores are shown in Figure 6.

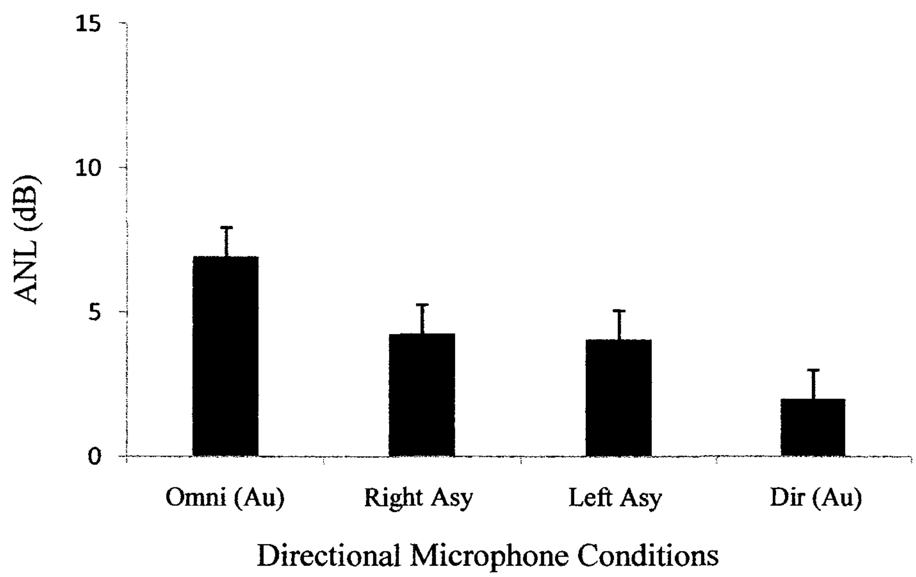

Figure 6 Mean ANL scores and standard deviations for four microphone conditions for the right and left ears.

A one-way repeated measure analysis of variance (ANOVA) was performed to evaluate the effects of microphone condition on acceptance of background noise. The dependent variable was the ANL. The within subjects factor was microphone condition with four levels (binaural omnidirectional, right asymmetric, left asymmetric, and binaural directional). The analysis revealed a significant main effect for microphone condition ($F[3, 42] = 32.613$, $p < 0.001$). Furthermore, post hoc analyses were conducted using pairwise comparisons; a Bonferroni adjustment was applied for multiple comparisons.

Pairwise comparison results revealed ANLs for the binaural omnidirectional fitting was significantly larger (i.e., worse) than the ANLs for the two asymmetric directional conditions and the binaural directional condition. Moreover, ANLs for the two asymmetric directional microphone conditions were not significantly different from one another. Furthermore, ANLs for the binaural directional condition were lower (i.e., better than either asymmetric microphone condition or the binaural omnidirectional microphone condition (see Table 2).

Table 2

Post hoc analysis comparing mean ANL scores for each microphone condition.

Microphone Condition	ANL scores
Binaural Omnidirectional	$6.93_{A, B}$
Asymmetric Directional (R)	4.26_{A}
Asymmetric Directional (L)	4.06_{B}
Binaural Directional	2.00_{C}

Note: Any two means in the same column with the same subscript are significantly different.

These results indicated listeners fitted with asymmetric directional fittings are more likely to accept their hearing aids than listeners fitted with binaural omnidirectional microphones. The results further revealed that no significant differences were found between the two asymmetric directional microphone fittings, indicating that acceptance of background noise was not affected by the location of the directional microphones (i.e., on the right or left ear). Lastly, the results indicated that listeners' willingness to wear hearing aids (i.e., accept hearing aids in the presence of background noise) is maximized when utilizing binaural directional microphones when compared to both asymmetric directional and omnidirectional fittings.

CHAPTER V

DISCUSSION

Test Box Measures

Test box measures were performed using each subject's audiometric data and hearing aid settings. These measures revealed that response curves varied in the predicted direction when directivity was applied (see Figure 2). Specifically, the response curves showed that the binaural omnidirectional front and back conditions were similar. Furthermore, the response curve of the directional back condition was significantly reduced compared to that of the directional front condition. These results suggested that the hearing aids were functioning appropriately throughout the experimental testing. The results were expected based on benefit obtained from of directional microphones reported by Freyaldenhoven, Nabelek et al. (2005).

Freyaldenhoven, Nabelek, et al. (2005) reported mean front to back ratios (FBRs) when using directional microphones of 2.91 dB with a range from -2 to 11 dB. Additionally, results from the present study indicate that the benefit received from directional microphones can be measured using routine, clinical probe microphone measurements like the directional measurement on the Audioscan Verifit.

Speech Understanding in Noise

One purpose of the present study was to determine the effect of asymmetric directional microphone fittings on speech understanding in noise. Fifteen adults with bilateral SNHL participated in this study. The results revealed a significant improvement in speech in noise scores when listeners were fit with either asymmetric directional or binaural directional microphones compared to binaural omnidirectional microphones. Additionally, results of the present study revealed that speech understanding in noise scores were not significantly different when the directional microphone was fitting on the right versus the left ear. These results suggest that speech understanding in noise scores are not affected by the location of directional microphone for patients with symmetric hearing loss (i.e., asymmetric right and left scores were not different). Furthermore, no substantial differences were found between speech in noise scores when listeners were fit with either asymmetric directional microphones (right or left) or bilateral directional microphones, indicating that speech understanding in noise scores are not degraded when using asymmetric directional microphones compared to bilateral directional microphones.

These results were expected based on previous research by Bentler et al. (2004) and Cord et al. (2007). First, Bentler et al. (2004) examined the effects of directivity index (i.e., a measure of directional benefit which compares sounds coming from the front to sounds originating from all other locations) on speech perception in noise and sound quality judgments. The results indicated that performance in noise was degraded when using an omnidirectional hearing instrument compared to asymmetric or directional hearing instruments; however, no substantial differences were seen in speech understanding abilities when asymmetric and directional microphones were used. Based on these results, Bentler et al. (2004) concluded that asymmetric directional microphone fittings do not significantly hinder listeners' speech understanding in noise. In a similar study, Cord et al. (2007) reported the effects of asymmetric directional microphone fittings in real life listening situations. Specifically, Cord et al. (2007) found that the listeners fit with bilateral omnidirectional microphones fittings showed poorer speech recognition in noise scores compared to the binaural directional or asymmetrical modes; however, no significant differences were seen between speech in noise scores for the binaural directional and asymmetrical microphone modes. Moreover, results of study showed that greater ease of listening was reported in the majority of listeners fit with the asymmetric directional microphones than the listeners with binaural omnidirectional microphones when listening in noise. These results indicated that an asymmetrical directional hearing aid fitting may be a practical option to improve listeners' ease of listening ability in quiet and in noise.

Acceptance of Background Noise

Another purpose of the study was to determine if asymmetric directional microphone fittings affected acceptance of background noise. Results of the present study revealed that ANLs for the two asymmetric directional conditions were lower (i.e., better) than ANLs for the binaural omnidirectional microphone condition. Results further revealed no significant differences for ANLs between the two asymmetric conditions. Lastly, the results revealed ANLs were lower (i.e., better) in the directional condition compared to either the asymmetric directional or binaural omnidirectional conditions. Because ANLs are directly related to hearing aid acceptance, these results indicated that listeners' willingness to wear hearing aids in the asymmetric directional mode may be increased compared to binaural omnidirectional microphone fittings. Furthermore, these results indicate that acceptance of background noise was not substantially affected by the location of directional microphone, at least for people with symmetric SNHL. Lastly, these results indicated that the use of binaural directional microphones maximizes listeners' willingness to wear hearing aids (i.e., acceptance of hearing aids) when compared to both asymmetric directional and binaural omnidirectional fittings. It should be noted that for this experiment speech was presented from the front while noise was presented from directly behind the listener. Therefore, these results should be viewed with caution when the noise is orientated from other directions.

Furthermore, it was expected that ANLs would decrease when the hearing aids were changed from the binaural omnidirectional condition to the directional microphone condition based on the results reported by Freyaldenhoven, Nabelek et al. (2005). Freyaldenhoven, Nabelek, et al. (2005) showed an average ANL decrease of 3.50 dB when comparing ANLs obtained while listeners wore two omnidirectional hearing aids versus ANLs obtained when listeners wore two directional hearing aids, indicating that listeners accepted more noise when using directional microphones over omnidirectional microphones in their hearing aids. In the present study, an average ANL decrease of 4.93 dB was seen when comparing ANLs obtained using the binaural omndirectional microphones versus those obtained when using binaural directional microphones.

Results of the current study further revealed an average ANL increase (i.e., ANLs worsened) of 2.26 dB for the right asymmetric microphone condition and 2.06 dB for the left asymmetric directional microphone condition compared to the binaural directional microphone condition. Stated differently, an average ANL decrease (i.e., ANLs improved) of 2.67 dB for the right asymmetric microphone condition and 2.87 dB for the left asymmetric directional condition was found when compared to the binaural omnidirectional microphone condition. In other words, ANLs for the asymmetric directional microphone conditions were about half way in between ANLs for both the binaural omnidirectional and directional microphone fittings. These results suggest that when listeners are fitted with asymmetric directional microphones their willingness to wear hearing aids may decrease compared to binaural directional microphone fittings and increase compared to the binaural omnidirectional microphone conditions. Based on these results, the authors agree that the fitting of asymmetric directional microphones may be a practical option for patients that are unable or unwilling to change their hearing aids to the directional microphone program.

Clinical Implications

Results of the present study indicated that asymmetric directional fittings increase speech understanding in noise compared to binaural omnidirectional fittings and did not significantly hinder listeners' speech understanding in noise when compared to binaural directional microphone fittings. These results indicate that asymmetric directional microphone fittings may be practical and beneficial to the listeners who are unable or unwilling to change their hearing aid programs from omnidirectional to directional in daily listening situations. Furthermore, results of the study revealed that speech understanding in noise scores for the two asymmetric directional microphone fittings were not significantly different from one another. These results indicated that listeners' performance in noise may not be influenced by the location of directional microphone, at least when the noise is coming from directly behind the listener. More importantly, these results indicated that either ear may be fitted with directional microphones for patients with symmetrical SNHL.

Moreover, results of the present study revealed that ANLs for the two asymmetric directional fittings were lower (i.e., better) than ANLs for the binaural omnidirectional microphone condition, indicating that asymmetric directional microphone fittings may increase listeners' acceptance of background noise, thus increasing listeners' willingness to wear hearing aids. ANLs for the two asymmetric directional microphone conditions were not significantly different from one another, indicating that the listeners' willingness to wear hearing aids may not be influenced by the ear that the directional microphone is fit. Lastly, ANLs for the binaural directional microphone condition were lower (i.e., better) than either the asymmetric or omnidirectional microphone conditions, indicating that binaural directional microphone fittings increase listeners' acceptance of background noise maximally, thus maximally enhancing their willingness to wear hearing aids. It should be noted that for the current study, speech was delivered directly in front while noise was delivered from directly behind the listener; therefore, these results may vary when the noise source is varied.

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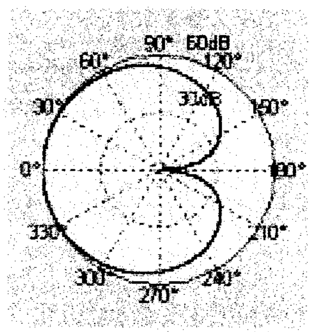
APPENDIX A

POLAR PLOTS

CARDIOID



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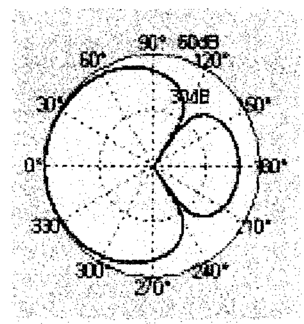

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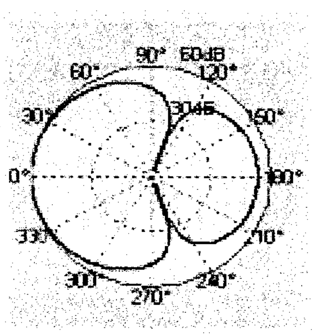
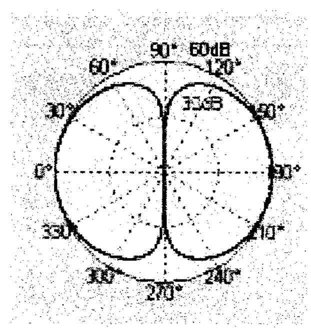


BIDIRECTIONAL



APPENDIX B

ACCEPTABLE NOISE LEVEL INSTRUCTIONS

Prior to the measurement of ANLs, each subject's hearing aids will be set to one of the four directional microphone modes by pushing the program buttons: binaural omnidirectional microphone mode, right asymmetric directional mode, left asymmetric directional microphone mode, and binaural directional microphone modes.

Instructions for Establishing MCL:

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. Two hand-held buttons will allow you to make adjustments. First, turn the loudness of the story up until it is too loud and then down until it is too soft. Finally, select the loudness level of the story that is most comfortable for you.

Instructions for Establishing BNL:

You will listen to the same story with background noise of several people talking at thesame time. After you have listened to this for a few moments, select the level of background noise that is the most you would be willing to accept of "put-up-with" without becoming tense and 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 maximum noise level that you would be willing to "put-up-with" for a long period of time while following the words of the story.

APPENDIX C

INFORMED CONSENT FORM

HUMAN SUBJECTS PERMISSION FORM
Experimental Group

The following is a brief summary of the project in which you have been asked to participate. Please read this information before signing below:

TITLE: Effect of Asymmetric Directional Microphone Fittings on Acceptance of Background Noise

PURPOSE OF STUDY/PROJECT: This research study is designed to investigate the effects of asymmetric directional microphone fittings on acceptance of background noise in hearing aid users.

PROCEDURES: If you volunteer to participate in this study, you must agree to have a hearing evaluation, which will be provided by the Louisiana Tech University Speech and Hearing Center free of charge. The hearing includes basic tests of ear canal health, eardrum mobility, and hearing sensitivity. The audiologic test will take about 30 minutes. If the test results do not satisfy the subject eligibility criteria of the study, you will be excluded from further study participation. However, if the results of the test meet the subject eligibility criteria, you will be asked to perform the following things.

You will be fitted with two hearing aids using standard (one-size fits all) earmolds. Your hearing aid directional microphone modes will be altered; omni in the left ear and directional in the right ear or vice versa. A story will be presented at various levels. You will then be asked to adjust background noise to a level that is acceptable to you. All the sounds will be presented at a comfortable loudness level in a sound-treated booth. You will be offered frequent breaks during the test. This portion of the project will take approximately 1 hour and the completion of the entire project will take about 1.5 hours.

INSTRUMENTS: The subject's identity will be confidential throughout the study and will not be utilized in any form in the analysis or representation of the data.

RISKS/ALTERNATIVE TREATMENTS: There are no known risks to the subject. All testing procedures will be conducted at normal conversational speech levels and are similar to clinical audiometric measures. Participation is voluntary with informed consent. You are free to discontinue participation at any time.

BENEFITS/COMPENSATION: Each participant will receive a free audiologic evaluation and a hearing aid check, if applicable.

I, ______________________________, attest with my signature that I have read and understood the above description of the study, "Effect of Circuitry on Acceptable Noise Level Growth Patterns," and its purposes and methods. I understand that my and my participation in this research is strictly voluntary and my participation or refusal to participate in this study will not affect my relationship with Louisiana Tech University or Louisiana Tech Speech and Hearing Center. Furthermore, I understand that I may withdraw at any time or refuse to answer any questions without penalty. Upon completion of the study, I understand that the results will be freely available to me upon request. I understand that the results will be confidential, accessible only to the project director, principal experimenters, myself, or a legally appointed representative. I have not been requested to waive nor do I waive any of my rights related to participating in this study.

____ ________________________

Signature of Participant Date

CONTACT INFORMATION: The principal experimenter listed below may be reached to answer questions about the research, subject's rights, or related matters.

Melinda Freyaldenhoven, Ph.D., CCC-A, Jong Sik Kim, B.A. Department of Speech (318) 257-2146

Members of the Human Use Committee of Louisiana Tech University may also be contacted if a problem cannot be discussed with the experimenters:
Dr. Les Guice (318)257-4647 Dr. Mary Livingston (318)257-2292 Nancy Fuller (318)257-5075

APPENDIX D

HEARING AID FITTING PROCEURES

(SIEMES INTUIS-DIR)

1. Click on NOAH program
2. Search subject or client and save it
3. Click on audiogram and insert thresholds
4. Save the audiogram
5. Connect the hearing aids
6. Click on open module program: Siemens
7. Click on Detect
8. First Fit for- both HA/use same fitting strategy for both /traditional
9. Hit Next: Acclimation Level-4/ NAL-NL1/ VC-Default (0), # of programs:2+A
10. Hit Next
11. Venting-No Vent/ Earmold=Short/ Hook= Standard with damper
12. Apply 1st Fit
13. a) Go to Program #1(Universal)

    Click on Fine Tuning

    - Compression (Compression Kneepoint & Ratio- Turn to Off -both hearing aids)
    - Noise/FB/MIC:

-Unclick NR & FB

- Extra:
  -Unclick Volume Control

14. Go to Program # 2

Click on Fine Tuning

- Compression (Compression Kneepoint & Ratio- Turn to Off–both hearing aids)

- Change to noisy environment (default to the last tap on the bottom)

- Noise/Feedback/MIC

  -Unclick Noise Reduction/Feedback
  -Microphone System= Directional

- Extra:
  -Unclick Volume Control

15. Program the hearing aids

16. Save the program session with date

APPENDIX E

TEST BOX MEASURES

1. Turn on power supply
2. Click Test
3. Click Hearing Instrument Test Calibration
4. Open test box and line up reference microphone and coupler microphone
5. Close loud speaker lid and hit Calibration
6. You should get a relatively flat line
7. Attach the hearing aid to the BTE coupler and turn the Volume Control full-on
8. Line up BTE hearing aid reference microphone
9. Click Directional under Hearing Instrument
10. Presentation: Single view
11. Format: Graph
12. Scale: dB SPL
13. Choose Dual Noise and Hit 65dB

APPENDIX F

HEARING IN NOISE TEST

INSTRUCTIONS

Prior to the measurement of HINT, each subject's hearing aids will be set to one of the four directional microphone modes by pushing the program buttons: binaural omnidirectional microphone mode, right asymmetric directional mode, left asymmetric directional microphone mode, and binaural directional microphone modes.

Instructions for Establishing HINT

You will listen to 8 lists of 10 sentences (each list is composed of 10 sentences) with background noise through the loudspeakers. I want you to repeat the sentences that you heard. After you have listened to two lists of 10 sentences, I will change your hearing aid program modes.