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The effects of noise reduction technologies on the acceptance of background noise

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To the Graduate Council:

I am submitting herewith a dissertation written by Kristy Jones Lowery entitled "The effects of noise reduction technologies on the acceptance of background noise." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Speech and Hearing Science.

Patrick N. Plyler, Major Professor

We have read this dissertation and recommend its acceptance:

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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and recommend its acceptance:

James W. Thelin

Deborah von Hapsburg

Jim Hall

Accepted for the Council:

____
Carolyn R. Hodges
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The Effects of Noise Reduction Technologies on the Acceptance of Background Noise

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Kristy Jones Lowery
May 2009

ABSTRACT

The effect of noise reduction technologies in hearing aids on a listener's acceptable noise level (ANL) was investigated. Technology designed to reduce noise within hearing aids; directional microphones (D-Mic), digital noise reduction algorithms (DNR) and the combination of the two technologies (Combo) were employed in the presence of three distinctly different background noises (single talker speech, speech shaped noise, and multi-talker babble). The same pair of twelve channel wide dynamic range compression behind-the-ear hearing instruments was fit on each of thirty participants. The hearing aids were set with four memories: no noise reduction technology activated (baseline), only D-Mic activated, only DNR activated, and the Combo of technologies activated. All other hearing aid settings and features remained the same across memories. Acceptable noise levels were investigated in each memory in the presence of each noise. In addition, subjective preference rankings of the noise reduction technology were obtained within each background noise (1= best, 3=worst). Listeners yielded significantly lower (better) ANL scores with Combo relative to D-Mic and DNR; and scores obtained with D-Mic were significantly better than those obtained with DNR. A technology x noise interaction was observed only for speech shaped noise in DNR, with listeners accepting significantly more noise in the presence of speech shaped noise than background noise containing speech. Listeners preferred D-Mic and Combo programs significantly more than DNR in the presence of single talker and multi-talker babble, and preferred Combo significantly more in the presence of speech shaped noise. Overall, listeners preferred the D-Mic and Combo programs equally as much and significantly more than DNR. In reviewing the preference data along with the ANL data, it is evident that improving an ANL with hearing aid technology is noticeable to listeners, at least when examined in this laboratory setting. These results indicate that listeners prefer noise technologies that improve their ability to accept noise.

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I. INTRODUCTION

Hearing loss affects an estimated 31.5 million people in the United States (Kochkin, 2005). With no corrective treatment for a vast majority of those afflicted, the most viable treatment option is hearing aids. In addition to amplifying desired sounds such as speech, hearing aids also amplify undesired sounds such as background noise. Not surprising, one of the most common complaints of persons fitted with hearing aids involves the adequacy of perceiving speech in the presence of background noise (Plomp, 1978; Dubno, Dirks & Morgan, 1984; Festen & Plomp, 1990; Souza & Turner, 1994; Needleman & Crandell, 1995; Killion, 1997). Of individuals with hearing loss, only 20% own hearing aids. Of these hearing aid owners, approximately 30% are dissatisfied while 17% never use their hearing aids (Kochkin, 2005).

From the inception of digital hearing aids in the late 1970s (Levitt, 2007), technology has evolved expeditiously. In order to meet the goal of communication restoration, these advancements have focused on not only aiding speech, but concomitantly dealing with various background and ambient noises found bothersome to hearing aid users. Two such technologies designed to alleviate the effects of background noise are directional microphones and digital noise reduction algorithms.

Directional microphones were introduced to the United States hearing aid market in the early 1970s (Ricketts, 2005). Simply stated, the goal of directional microphone technology in a hearing aid is to attenuate sounds arriving at the hearing aid microphone from anywhere other than the front of the listener. While the literature is replete with investigations citing improved signal-to-noise ratio (SNR) with directional microphones (Valente, Fabry & Potts, 1995; Valente, Schuchman, Potts & Beck, 2000; Gravel, Fausel, Liskow & Chobot, 1999; Preves, Sammeth & Wynne, 1999; Ricketts & Dhar, 1999; Wouters, Litiere & van Wieringen, 1999), it should be noted that a vast majority of the research has been conducted in a laboratory setting, with the findings dependent upon the number and location of speakers; the type, level and distance of the noise source; the reverberation characteristics of the environment; and the amount of low-frequency compensation provided (Amlani, 2001). Results have varied from little or no directional advantage (Valente, Fabry & Potts, 1995) to a directional advantage of 16.4 dB (Dybala, 1996). Because the hearing aid wearer must position themselves so they are facing the sound source of interest, with undesired sounds behind them in order to gain maximum benefit from the technology, (Ricketts, Henry & Gnewikow, 2003), limitations of the technology include environments with pervasive, surrounding noise and situations with multiple speakers of interest.

While objective measures of directional microphones have suggested improved speech perception when measured in the laboratory relative to omnidirectional microphones, subjective data have been inconclusive. In 2002, Cord, Surr, Walden and Olson evaluated performance of directional microphone hearing aids in “everyday life” and concluded that participants reported the same level of satisfaction with each microphone type (directional and omni-directional).

Furthermore, Palmer, Bentler and Mueller (2006) reported that, following a ten day trial with hearing aids employing automatic switching adaptive directional microphones, no preference emerged for directional microphone settings (fixed or adaptive) compared to the omni-directional setting. These data reveal that despite the overwhelming evidence of improved directional benefit in the laboratory (Ricketts, 2005; Preves et al., 1999, Boymans & Dreschler, 2000, Walden et al., 2000), the improvements are not as noticeable in everyday life. Given the limitations of directional microphones in diffuse listening situations, another form of noise reduction technology, digital noise reduction (DNR), is often used in combination with directional microphones in hearing aid fittings in an attempt to reduce the negative effects of background noise on communication.

Digital noise reduction technology has been available in hearing aids since the 1970s (Bentler & Chiou, 2006). The technology works primarily on the principle that physical characteristics of speech differ from physical characteristics of most noise-like stimuli, allowing for gain reductions of the noise-like input. While manufacturer implementation of DNR varies across manufacturers, all base a determination of gain reduction on analysis of the following aspects of the signal or environment: signal-to-noise ratio, input level, and amplitude modulation frequency and depth of the signal. These components can be assessed independently or in various combinations to establish rules regarding how much and in what channels gain reduction should occur (Bentler & Chiou, 2006). Research is limited regarding the real world effectiveness of DNR in hearing aid fittings, and much of the research investigates DNR in combination with directional microphones. Boymans and Dreschler (2000) concluded that hearing aid wearers received no extra objective benefit as measured by improvements in speech intelligibility from the combined use of directional microphones and noise reduction compared to directional microphones alone. Although the goal of DNR is to improve speech perception performance, objective evidence suggests that DNR results in subjective benefit such as greater sound comfort and quality (Boymans & Dreschler, 2000; Walden, Surr, Cord, Edward & Olson, 2000). Conversely, directional microphones, which have been documented to improve objective benefit as measured by improvements in speech intelligibility, are not subjectively preferred by listeners relative to omni-directional microphones. As such, it appears that speech intelligibility may not influence a listeners' subjective preference for a hearing aid and therefore may not be the best predictor of a successful hearing aid fitting. Recent research has focused on investigating a measure that allows for accurate prediction of hearing aid success.

Acceptable noise level (ANL) was first introduced by Nabelek, Tucker and Letowski (1991) in an attempt to quantify, using a quick and easy procedure, the amount of background noise a listener is willing to tolerate while listening to speech. The premise of the ANL measure is that a person's willingness to listen in noise may be more important than their ability to understand in noise for successful use of hearing aids (Nabelek et al., 1991). Acceptance of noise is measured as the difference between speech presented at the individual's most comfortable listening level (MCL) and the highest background noise level (BNL) that is acceptable while listening to and following a speech sample. Therefore, ANL = MCL- BNL (all expressed in dB). Consequently, listeners with low ANL scores accept more background noise when listening to speech while listeners with high ANL scores accept less background noise when listening to speech. Research has shown that unaided ANL scores serve as accurate predictors of hearing aid use. Successful hearing aid users accept higher levels of background noise (i.e., have smaller ANLs) than unsuccessful hearing aid users, regardless of their ability to understand speech in noise (Nabelek, Freyaldenhoven, Tampas, Burchfield & Muenchen, 2006). Therefore, ANL scores measured prior to hearing aid fittings may provide relatively strong predictors of individual success with hearing aids. Furthermore, if technologies designed to alleviate the effects of background noise improve one's ANL, ANL scores measured prior to hearing aid fittings may provide justification for fitting patients with certain hearing aid technologies.

Directional microphones and digital noise reduction (DNR) technologies approach noise reduction differently and are often used together to deal with noise in a hearing aid fitting. The effectiveness of a directional microphone is dependent on the location of the noise source. DNR algorithms attenuate sounds that have amplitude modulation patterns that are consistent with noise, while maintaining amplification for sounds that have amplitude modulation patterns that are consistent with speech. Thus, the effectiveness of a DNR algorithm is dependent on the temporal properties of the input, regardless of the sound-source location. To date, limited research has been conducted to investigate the effects of these noise reduction technologies on ANL.

Directionality and ANL

Freyaldenhoven, Nabelek, Burchfield and Thelin, (2005), examined directional microphones in regards to ANL and suggested that directional microphones resulted in significant benefit to a listener's ANL compared to an omni-directional microphone. Freyaldenhoven et al., (2005) tested 40 participants using their own instruments with commercially available directional microphone technology. The subjects listened to speech from a loudspeaker at 0^{o} azimuth and multi-talker babble from another loudspeaker at 180^{o} azimuth. ANLs for omni-directional and directional microphone settings were compared. For this simple loudspeaker array, the average benefit of directionality, expressed as a decline in ANL, was 3.5 dB. This benefit was comparable to the 3.6 dB benefit measured as an improvement in masked SRT. While larger directionality benefits in SRT were reported for multiple array loudspeakers, it appears that even with the simple two-loudspeaker arrangement, benefit can be demonstrated with the ANL measurements.

While the aforementioned research provides promising insight regarding the use of directional microphone technology to improve acceptance of noise, several limitations of this study should be addressed in future research. First, the primary goal of Freyaldenhoven et al., (2005) research was not to measure maximal directional benefit, but was to assess the clinical viability of the ANL procedure for measuring directional benefit. Consequently, participants were tested using their personal hearing aids, which did not control for factors known to affect directional benefit such as hearing aid style, type of directional microphone, vent size, compression, or low-frequency gain compensation (Ricketts, 2000a; 2000b). As a result, the variability in ANL benefit with directionality was relatively large and ranged from -4 to 12 dB. Subsequent research indicated that the large between-subject variability in ANL benefit with directionality was not attributed to venting and/or low-frequency gain compensation (Freyaldenhoven, Plyler, Thelin, Nabelek & Burchfield, 2006); however, a systematic, well-controlled evaluation of the effects of directionality on ANL remains needed.

Second, previous research indicates that ANL values are not affected by the type of background noise used (Nabelek et al., 1991); however, the effect of background noise type on ANL benefit with directionality has not been examined. The amount of directionality provided by any directional microphone varies as a function of frequency (Ricketts, Henry & Hornsby, 2005) and may be further impacted by venting and/or low frequency gain compensation (Freyaldenhoven, Plyler, Thelin, Nabelek & Burchefield, 2006). For example, Ricketts et al., (2005), demonstrated that directivity index values are greater for low frequencies than high frequencies. Therefore, spectral differences that exist between various background noise types could affect ANL values when using directional microphones. Thus, a systematic, well-controlled evaluation of the effects of background noise type on ANL benefit with directionality remains needed.

Third, the effect of ANL benefit with directionality on subjective outcome has not been evaluated. Although research suggests that successful hearing aid users accept higher levels of background noise (i.e., have smaller ANLs) than unsuccessful hearing aid users, what remains unclear is if improving an individual's ANL with directionality results in greater hearing aid acceptance. If subjective outcome relates to the condition that provides the lowest (best) ANL, attempting to improve an ANL with technology would clearly be a worthy goal. Thus, a systematic, well-controlled evaluation of the effects of ANL benefit with directionality on subjective outcome remains needed.

Digital Noise Reduction and ANL

Mueller, Weber and Hornsby, (2006), assessed both speech intelligibility and ANL with and without DNR and concluded that DNR significantly improved (lowered) a listener's ANL. The Hearing in Noise Test (HINT) was administered with DNR-on and DNR-off. In order to directly compare the acceptance of noise and speech intelligibility, HINT stimuli (male speaker in speech-shaped noise) were used to gather both the ANL and HINT. A significant improvement in ANL (decrease in ANL score) was reported when DNR technology was on relative to when it was off; however, no improvement in speech intelligibility was observed (DNR-on or DNR-off). It was therefore suggested that DNR can result in improved ease of listening for speech-in-noise due to the significant improvement in ANL. These data not only support previous research in that no observed improvement in objective benefit was noted with DNR, as measured by speech intelligibility, but also support previous findings that ANL is not related to, nor is it a task of speech intelligibility in noise

(Nabelek, Tampas & Burchfield, 2004).

While the aforementioned research provides promising insight regarding the use of DNR technology to improve acceptance of noise, several limitations of this study should be addressed in future research. First, it is possible that ANL improvements with DNR are attributed to methodological differences used by Mueller et al., (2006). When obtaining ANLs using the Nabelek et al., (1991) procedure, listeners are asked to make perceptual judgments while listening to continuous speech in the presence of continuous background noise. In contrast, when obtaining ANLs using the Mueller et al., (2006) procedure, listeners are asked to make perceptual judgments while listening to interrupted speech samples in the presence of continuous background noise. It is possible subjects made perceptual judgments when listening between speech samples (in noise alone) instead of while the speech was presented (as instructed). Given the fast attack time for the DNR used, noise levels could have been reduced during the pauses of speech and could have resulted in improved ANL values. Consequently, it is possible that ANL improvements with DNR are attributed to noise reduction during pauses of speech. What remains unclear, however, is if DNR can improve an individual's ANL when listening to continuous speech in the presence of continuous noise.

Second, previous research indicates that ANL values are not affected by the type of background noise used (Nabelek et al., 1991); however, the effect of background noise type on ANL benefit with DNR has not been examined. The amount of noise reduction provided by any DNR algorithm varies as a function of noise type. For example, Mueller and Ricketts, (2005) demonstrated that DNR is more effective for steady-state noises than noises containing speech. Therefore, temporal differences that exist between various background noise types could affect ANL values when using DNR systems. Thus, a systematic, well-controlled evaluation of the effects of background noise type on benefit with DNR remains needed.

Third, the effect of ANL benefit with DNR on subjective outcome has not been evaluated. Although research suggests that successful hearing aid users accept higher levels of background noise (i.e., have smaller ANLs) than unsuccessful hearing aid users, what remains unclear is if improving an individual's ANL with DNR results in greater hearing aid acceptance. If subjective outcome relates to the condition that provides the lowest (best) ANL, attempting to improve an ANL with technology would clearly be a worthy goal. Thus, a systematic, well-controlled evaluation of the effects of ANL benefit with DNR on subjective outcome remains needed.

Directionality + Digital Noise Reduction and ANL

Although the combination of directionality and DNR has been researched in terms of objective benefit (speech intelligibility) and subjective outcome (Boymans & Dreschler, 2000; Walden et al., 2000) it remain unclear how the combination of these features affect ANL. As previously mentioned, type of background noise has not been shown to affect ANL (Nabelek et al., 1991); however, the technologies under investigation are affected by the spatial and/or physical characteristics of sound. Therefore, how the technologies affect ANL in the presence of different background noises merits investigation. Also, the research investigating directionality and DNR with ANL has not examined the effects of ANL on subjective outcome. An investigation on subjective outcome relative to the effects of technology on ANL is thereby warranted. Given the conclusions regarding directionality and DNR independently on ANL, it is reasonable to postulate that using a combination of d-mics and DNR could further affect an ANL measure. However, questions still remain regarding how these technologies independently affect ANL.

The proposed experiment will involve a systematic investigation whereby the same pair of behind-the-ear hearing aids will be fit by the same audiologist to each participant, eliminating technological and programming differences among hearing aids. In addition, the subjective preference of directional microphones and digital noise reduction on ANL will be assessed within a controlled environment under different noise conditions. Therefore, the purpose of this experiment is to determine the effects of various noise reduction technologies on the acceptable noise level (ANL). The goal of this work is to determine if such technologies can improve a listener's acceptance of noise and to determine if these changes correspond to subjective preference. Although ANL research clearly indicates that listeners with low ANLs are more likely to be successful hearing aid users than listeners with high ANLs, the current ANL research is not clear in the area of features designed to combat noise (noise reduction features), particularly with regards to subjective outcomes resulting from an improved ANL. If subjective outcome relates to the condition that provides the lowest (best) ANL, attempting to improve an ANL with technology would clearly be a worthy goal. Therefore, the following research questions will be addressed:

- (i) Is acceptance of noise affected when using noise reduction technologies (D-mics, DNR, D-mics + DNR)?
- (ii) Is acceptance of noise affected by noise type when using noise reduction technologies?
- (iii) Do listeners prefer the noise reduction condition that results in the best ANL value?

II. REVIEW OF LITERATURE

General Overview

Hearing Aids and Noise Reduction

While the goal of amplification is communication restoration, a side effect is amplifying undesired sounds such as background noise in addition to sounds of interest, namely speech. Unfortunately, this undesired effect often leads to hearing aid rejection. In order to alleviate the effects of background noise on amplification, directional microphones and digital noise reduction are often implemented in today's hearing aid fittings. These two systems function differently from one another and are often used in combination to alleviate the effects of background noise (Bentler, 2005).

Noise Reduction Features in Hearing Aids

Directional Microphones

Directional microphones are designed to provide attenuation of sounds arriving from angles other than the front of the listener. This is accomplished by the physical separation of two microphone ports, which allows for signal separation based on arrival time of the signal at each of the ports. In order for sound reduction to occur, the external delay caused by the physical distance between the microphone ports must be met by an internal delay. The amount of attenuation occurring depends on the relationship between the two delays as well as the environmental sound sources. Some limitations of the technology include diffuse listening environments (those in which noise is surrounding the listener), an inability of the listener to face the speaker of interest, and conditions in which there are multiple speakers of interest and/or reverberant environments. And, while laboratory data show objective benefits with directional microphones, this benefit has not been shown to correlate with perceived benefit in the real world (Ricketts, 2005).

Valente, Schuchman, Potts and Beck (2000), investigated 50 adults with mild to moderately-severe sensorineural hearing loss using both omni-directional and directional microphone technology. Subjects wore hearing aids for 4 weeks prior to testing in order to account for acclimatization effects. Objective testing of speech perception was completed using the Hearing in Noise Test (HINT), which yields a signal to noise ratio (SNR) score at which 50% performance is obtained. The test was administered under two, counter-balanced conditions: speech at 0-degree azimuth, noise at 180-degree azimuth (ideal); and speech at 0-degree azimuth, noise at 45, 135, 225 and 315-degree azimuth (diffuse). Results revealed a mean directional microphone advantage of 3.3 dB, which was significantly better than the mean SNR for the omni-directional microphone. In addition, the mean SNR for the ideal listening situation was statistically better than the mean SNR for the diffuse situation. This research was in agreement with previous work investigating the effects of directional microphones on SNR values in different listening environments.

While objective testing with directional microphones yield improved SNR, subjective testing, namely in real world settings, has been inconclusive. Cord, Surr, Walden and Olson (2002) interviewed hearing aid wearers who were fitted with switchable omni-directional/directional configurations. Via telephone and paper-and-pencil questionnaires they were asked about use patterns and asked to compare perceived performance between the two microphone types in a variety of listening environments. Results revealed that most patients fitted with switchable omnidirectional/directional hearing aids do not utilize their directional program. Those patients who reported regularly using directional microphones did show preference for the directional mode in some environments, but reported that it was less helpful than the omni-directional mode when noise was diffuse and when reverberation increased. It was therefore concluded that specific characteristics of listening situations dictate perceived benefit of directional technology. Despite the perception of benefit in certain environments however, patients reported the same level of overall satisfaction with each microphone type.

Digital Noise Reduction

Digital noise reduction (DNR) is designed to reduce hearing aid output in the presence of noise. This is accomplished many different ways by different hearing aid manufacturers, but in general, continual assessment of the spectral, temporal and level characteristics of environmental sounds serves to control the implementation of DNR. Manufacturers not only differ in how DNR is activated, but also in how much attenuation should occur and where it should occur (in what channels). Due to the large variance in manufacturer implementation, environment plays a key role in activation of the feature and therefore patient benefit. And, while DNR was designed to help with speech intelligibility in the presence of noise, research has shown no extra objective benefit from DNR in such situations. Research has suggested that the use of DNR may result in greater sound comfort and quality relative to no DNR (Bentler & Chiou, 2005).

Ricketts and Hornsby (2005) examined the effect of DNR on speech recognition and sound quality perception in 14 adults. Speech recognition was examined at two levels: 71 dBA speech, +6 SNR; and 75 dBA speech, +1 SNR with DNR-on and DNR-off. Each participant was fitted bilaterally with the same model of behind-the-ear hearing aids. Speech recognition was evaluated using the Connected Speech Test (CST). The noise stimulus accompanying the CST was time-varied to create four different noises. Findings revealed DNR did not significantly affect speech recognition performance; however, listeners significantly preferred DNR-on versus DNR-off.

The objective and subjective benefits of DNR were assessed by Walden, Surr, Cord, Edwards and Olson (2000). In this study, 40 hearing impaired adults who were current users of bilateral hearing aids were fit with behind-the-ear digital hearing instruments implementing both DNR and directional microphones. Objective testing was completed using the CST and subjective ratings were compiled using the Profile of Hearing Aid Benefit (PHAB). Results revealed that DNR did not contribute any more or less to objective outcomes than the directional microphone mode, and that the noise reduction circuit provided improved listening comfort but little change in speech perception.

Acceptable Noise Level

A listener's acceptance of noise was first examined in 1991 by Nabelek, Tucker and Letowski. Then termed tolerated signal-to-noise ratio, the method was derived in order to quantify an individual's willingness to listen to speech in the presence of background noise. Now termed acceptable noise level (ANL), the measure is obtained by adjusting the level of running speech to a listener's most comfortable level. Next, background noise is added to the running speech and is adjusted to the maximum level the listener is willing to "put up with without becoming tense or tired" while listening to the story. This level is termed the background noise level (BNL). The ANL is determined by subtracting the BNL from the MCL (MCL – BNL = ANL) and is expressed in dB. In the 1991 study, the toleration of background noise was examined in five groups of participants; young persons with normal hearing, elderly persons with relatively good hearing, elderly hearing-impaired full-time hearing aid users, elderly hearing-impaired part-time hearing aid users, and elderly hearing-impaired non-users(of their hearing aids). Most comfortable listening levels (MCL) of the first 2 groups were not significantly different; however, they were different for groups 3, 4, and 5 respectively. The tolerated S/N for each group was not related to age or hearing loss, and was independent of the MCL selected for listening to speech.

In 2006, ANL was examined as a predictor of hearing aid use. Nabelek, Freyaldenhoven, Tampas, Burchfield, and Muenchen investigated 191 participants who were binaurally fit with hearing aids. Participants were divided into one of three groups based on questionnaires regarding their hearing aid use patterns: full time, part time, and non-users. Results of this study revealed that ANLs were not dependent on gender, age, or pure tone average (PTA). Both unaided and aided ANLs were significantly correlated with hours of daily use. Acceptable noise levels and SPIN scores were not correlated in the unaided and aided conditions; however, the average unaided and aided SPIN scores were different across all three groups. Therefore, while SPIN scores determined the benefit of amplification for speech perception, ANL determined the differences between successful and unsuccessful hearing aid use. The ANL measure predicted hearing aid success with 85% accuracy. Thus, the ANL measure can be used to predict hearing aid success.

In addition to predicting if one would be successful with hearing aids, Nabelek et al., (2006) were also able to predict *how* successful. Using logistic regression, a listeners' probability of success with hearing aids was predicted as a function of their unaided ANL (Figure 1). As explained by Nabelek et al., (2006), in order to determine ones' probability of success, their unaided ANL should be located on the x-axis curve. Then, the corresponding number on the y-axis should be multiplied by 100. For example, if the listener has an unaided ANL of 5, their probability of success with hearing aids is almost 100%, wheras somone with an unaided ANL of 15 has nearly 0 chance of success.

Directional Microphones and Acceptable Noise Level

Freyaldenhoven, Nabelek, Burchfield, and Thelin (2005) investigated the ANL procedure as a measure of directional hearing aid benefit. Forty listeners binaurally

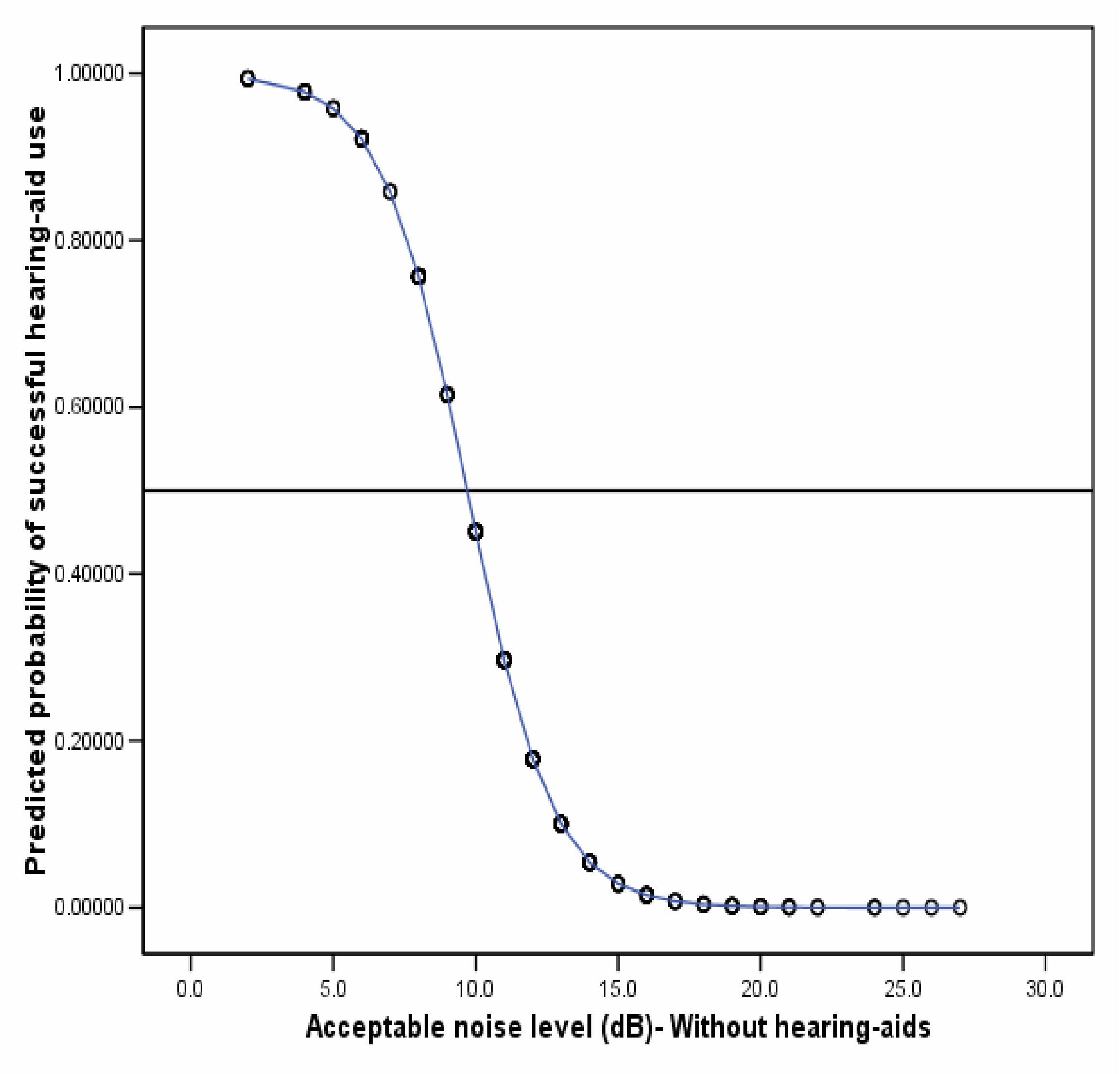

Figure 1. Probability of Success Curve, Nabelek et al., (2006).
Regression Analysis derived from 191 listeners to predict a listener's probability of success with hearing aids. Locating ones' unaided ANL on the x-axis, then multiplying the corresponding number on the y-axis by 100 yields a percentage of predicted probability of success.

fit with hearing aids (independent of the study) participated. The hearing aids had omni-directional and directional modes. Because the hearing aids were fit independent of the study, hearing aid style, type of directional microphone, vent size, compression, or low-frequency gain compensation were not controlled for. Each listener's ANL, front-to-back ratio (FBR) and masked speech recognition threshold (SRT) was obtained for each microphone mode. For each test, speech was presented to the listener from a loudspeaker a 0º azimuth and noise from 180º azimuth. For ANL and FBR testing, the speech stimulus was a recording of male running speech; for SRT, a male recording of spondee words. The noise stimulus for all testing was multi-talker speech babble. Results indicated that the average benefit of directionality, expressed as a decline in ANL, was 3.5 dB. This benefit was comparable to the 3.6 dB benefit measured as an improvement in masked SRT. Therefore, the ANL procedure was comparable to masked SRT and FBR when measuring hearing aid directional benefit.

Digital Noise Reduction and Acceptable Noise Level

The effects of digital noise reduction on ANL were investigated by Mueller, Weber and Hornsby in 2006. Twenty-two adults were each fitted with the same pair of bilateral, behind-the-ear wide-dynamic-range compression hearing aids with DNR processing. Each listener's speech intelligibility and ANL was assessed with DNR on and DNR off using the Hearing in Noise Test (HINT) stimuli. For both tests, speech and noise were present from the same loudspeaker at 0º azimuth. All participants received the HINT first, then the ANL test, with DNR on/off counterbalanced and randomly assigned for each test. Acceptable noise level was obtained by introducing continuous background noise to discrete sentences and having listener's make judgments regarding noise levels after each sentence was presented. Results revealed a significant mean improvement of 4.2 dB in ANL for the DNR-on condition compared to the DNR-off condition. The HINT score did not significantly correlate with ANL for either condition (DNR on or off). These findings suggested that DNR can significantly improve one's acceptance of background noise and therefore may result in improved ease of listening for hearing aid users.

III. METHODS

Listeners and Environment

Thirty adult listeners with sensorineural hearing impairment were recruited to participate in this experiment. Twenty-four males and six females with an average age of 65.5 (24-84) years participated. Twenty-three of the participants were experienced hearing aid users and seven were inexperienced users. A power analysis using Simple Interactive Statistical Analysis (SISA) revealed the sample size to be sufficient to demonstrate statistical power ($\alpha = .05$). Listeners for the experiment were selected from The University of Tennessee Hearing and Speech Center as well as the Knoxville community. The criteria for inclusion included: (i) sensorineural hearing impairment with no more than a 15 dB difference in pure tone thresholds at any octave frequency from 250 through 8000 Hz between ears (ANSI S3.6-1996); (ii) normal appearance of ear canal and pinna; (iii) no air-bone gaps greater than 10 dB. All qualification and experimental testing were conducted in a sound-treated examination room (Industrial Acoustic) with ambient noise levels suitable for testing with ears uncovered (ANSI S3.1-1991). Participation involved one testing session at The University of Tennessee.

Hearing Instruments

Each participant that met the aforementioned audiometric criteria (Figure 2) were fitted binaurally with Siemens, Artis 2 S/VC digital behind-the-ear hearing instruments (Siemens Hearing Instruments Inc, Piscataway, NJ), with wide dynamic

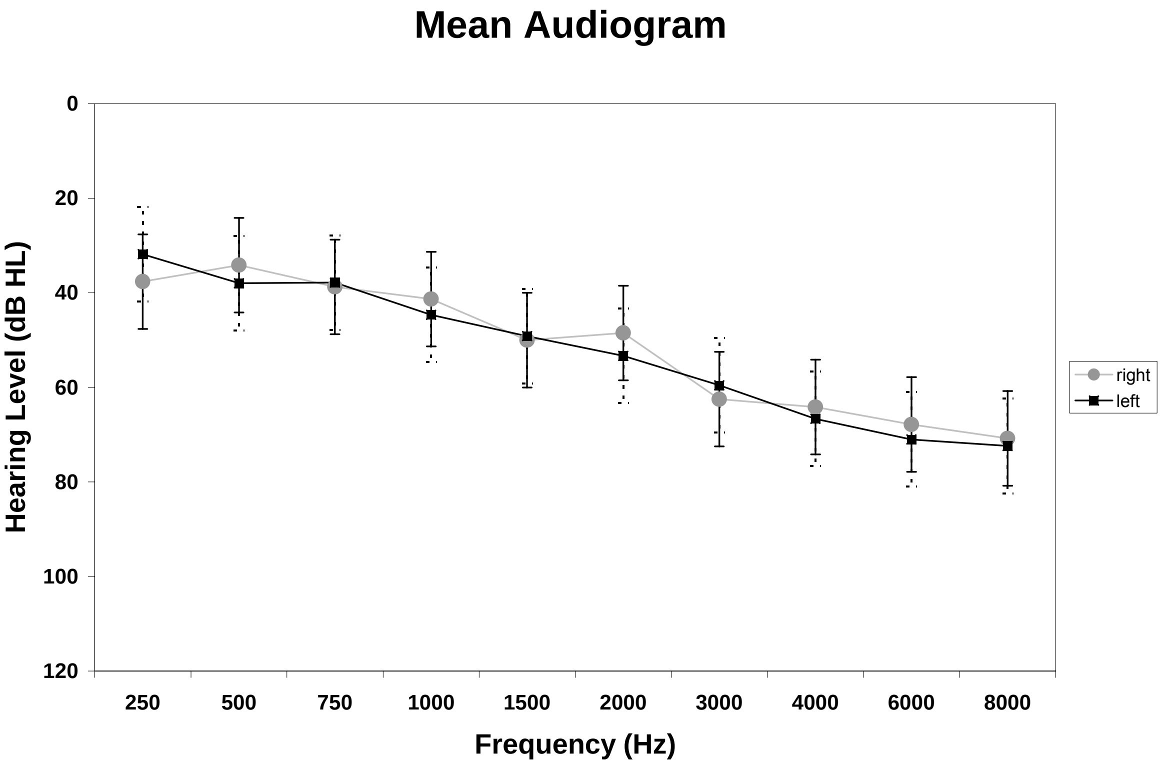

Figure 2. Mean Audiometric Data
Mean audiometric data, including standard deviations, from the 30 participants.

range compression processing and multiple memory capabilities. The hearing aids utilized for this project were consignment aids provided to the investigator by Siemens Hearing Instruments for research purposes. Therefore, the same two hearing instruments were used for each participant. The hearing aids employed 12 channel wide dynamic range compression. Features included multi-channel directional microphones, feedback cancellation, digital noise reduction, expansion, wind suppression, and volume control. Wind suppression and volume control were disabled for the duration of testing. Expansion and feedback cancellation remained enabled, as their functioning did not serve to interfere with or confound the effects of the features under investigation within the parameters of this investigation. The directional microphones and digital noise reduction were selectively enabled or disabled throughout testing. The hearing aids also had a feature allowing for continuous electromagnetic transmission between the instruments, ensuring that both hearing aids were operating in the same program/setting during testing.

The hearing instruments employed the same DNR algorithm investigated by Mueller et al., (2006), which allowed for direct comparison of results. The particular system utilized 2 different types of DNR algorithms, one modulation based, and one an adaptive fast-acting system, much like Wiener filter technology (Hamacher, Chalupper, Eggers, Fischer, Kornagel, Puder & Rass, 2005). The systems, described extensively by Hamacher and colleagues (2005), operate simultaneously and independently in all 12 channels of the aids. The modulation based algorithm analyzes the spectrum of the envelope in order to attenuate frequency components with very low signal-to-noise ratios whereas the adaptive fast acting system employs a 10 millisecond filter to track the signal envelope of each channel to provide inter-syllabic noise reduction.

Each participant was fit with the bilateral behind-the-ear hearing aids using foam Comply tips (Hearing Components, Inc, Oakdale, Minn). The hearing aids were initially programmed using proprietary fitting algorithm software, Siemens CONNEXX 5.0 version 1 (Siemens Hearing Instruments Inc). Probe microphone measures were conducted to verify match to NAL-NL1 targets (Byrne et al., 2001) for each participant. Three memories of the digital hearing instruments were programmed randomly for each participant: 1) directional microphone activated only (D-mic) 2) digital noise reduction activated only (DNR) 3) directional microphone and digital noise reduction activated simultaneously (Combo). In addition, each participant was tested with a baseline memory (omni-directional with DNR deactivated) prior to the instruments being programmed as described above. Each memory had identical fitting parameters except for the respective activation/deactivation of D-Mic and/or DNR. Prior to testing, probe microphone measures were conducted with the Verifit (Audioscan, Dorchester, Canada) using the Knowles Electronic Mannequin for Auditory Research (KEMAR) to ensure that the advanced features under investigation performed as expected. Also prior to data collection, an experimental schedule was generated for each participant listing a completely randomized assignment of memories. Following the verification and fitting of the instruments, testing commenced.

Test Materials

ANL was measured using the Nablek et al., (2004) procedure with running speech recorded by a male talker as the primary stimulus (Arizona Travelogue, Cosmos, Inc.). ANL was assessed with three separate types of background noise for each memory. The noises used are as follows: a single male talker using a recording of the Ipsilateral Competing Message from the Synthetic Sentence Identification with Ipsilateral Competing Message test (Speaks & Jerger, 1965); 12-talker speech babble (Revised SPIN recorded by Cosmos, Inc.; Bilger, Neutzel, Rabinowitz & Rzeczkowski, 1984); and speech-shaped noise from the Hearing in Noise Test (HINT). Previous studies have revealed that type of background noise does not affect acceptance of noise, with the exception of music (Nabelek et al., 1991); however, the effect of background noise type on ANL benefit with the aforementioned noise features has not been examined. Because the functioning of the features under investigation are dependent upon the spectral and temporal properties of the background noise, the noise types used in this study, spectrally and temporally different from one another, were therefore chosen to investigate the effects of noise features on the type of background noise and consequently on one’s acceptance of noise.

Procedures

ANL Procedure

A randomized testing schedule was generated for each participant to determine the order in which memories and noise conditions would be evaluated.

All speech stimuli and background noise were produced by a compact-disc player and routed through a two-channel diagnostic audiometer (GSI-61) calibrated to ANSI (ANSI, S3.6 – 1996) standards, to loudspeakers located at 0-degree and 180-degree azimuth. The speech stimuli were presented via an ear-level loudspeaker at 0-degree azimuth, and the background noises were presented via an ear-level loudspeaker at 180-degree azimuth in order to maximize the D-mic effects. Participants were seated 1 meter from the loudspeakers. Prior to data collection, participants were given oral and written instructions (Appendix1) for the ANL procedure. They were asked to indicate; via a hand-held button, how/when they wished the stimuli to be adjusted in intensity. The buttons, connected to a box with green (increase in intensity) and red lights (decrease in intensity) outside of the testing booth, allowed for the tester to know how to manipulate the stimuli. The intensity of the stimuli were manipulated in 5-dB steps initially and in 2-dB steps when selecting the final loudness level that was “most comfortable.” Once the participant’s most comfortable listening level (MCL) was established, background noise was introduced in the pre-determined order set forth by the randomized experimental schedule. The background noise was introduced at 30 dB HL, as suggested by Nabelek et al., (2004), and adjusted to the participant’s acceptable background noise level (BNL). BNL is defined as the level of background noise that can be tolerated, without becoming tense or tired, while listening to speech.

Each participant’s ANL was conducted two times in each memory: Baseline, D-mic, DNR, and Combo; and for each listening condition: running speech in the presence of a single talker, twelve-talker speech babble and speech shaped noise. An average of the two calculated ANLs served as the mean ANL for each listener in the given condition. Testing resulted in a total of 24 ANL measures for each participant.

Subjective Procedure

Following the completion of ANL testing, each participant was asked to subjectively evaluate the technology programmed into each memory. Prior to obtaining subjective evaluations, participants were given oral and written instructions (Appendix 2). Speech stimuli were presented from 0-degree azimuth and noise stimuli were presented from 180-degree azimuth at levels corresponding to each participant’s baseline ANL for the respective noise condition. For example, if a participant’s baseline ANL resulted from an MCL of 58 dB HL and a BNL of 39 dB HL for the single talker noise stimulus, the speech stimulus was presented at 58 dB HL, and the single talker noise stimulus was presented at 39 dB HL. After being given adequate time to listen to the stimuli in each program, participants were asked to rank the three memories, from 1 to 3, with 1 being the best and 3 being the worst. This ranking procedure was repeated for all three noise stimuli and resulted in 12 rankings for each participant. At the completion of the experiment, each participant was asked to indicate which setting they preferred overall to determine if the condition resulting in the most acceptance of background noise was reported as the preferred condition for each participant.

IV. RESULTS

ANL Procedure

Acceptable noise level scores within each memory and background noise listening condition were averaged across the 30 participants (Table 1). ANL scores were converted to benefit scores for each experimental condition for the 30 participants to determine if acceptance of noise is affected when using the technologies under test. Benefit scores were determined by subtracting the ANL scores obtained with each memory (D-Mic, DNR, Combo) from the baseline ANL score for each background noise (single talker, speech shaped noise, babble). For example, a participant with a baseline ANL score of 20 dB and a D-Mic ANL score of 5 dB would have an ANL benefit score of 15 dB for the given noise condition. Thus, positive values represent improvements in the ANL score when using the noise features. Nine benefit scores were calculated for each participant. Benefit scores were then averaged within experimental conditions across the 30 participants (Figure 3). The mean benefit score across noise type for each memory was as follows: DNR, 3.28 (-13 to 17); D-Mic, 5.3 (-8 to 19); and Combo, 7.01 (-8 to 21).

A two way Analysis of Variance (ANOVA) with repeated measures was performed to evaluate the effect of noise reduction technologies and background noise type on ANL benefit scores. The dependent variable was ANL benefit score. The within-subject factors were noise feature technology (D-Mic, DNR, Combo) and background noise type (single talker, twelve-talker babble, speech

Table 1. ANL Information. The mean, range and standard deviation of ANLs averaged across noise type for the 30 participants.

	Baseline	**DNR**	**D-Mic**	**Combo**
Single Talker	14.23, (-2 - 35), 8.38	11.67, (2 - 26), 6.51	8.50, (-5 - 26), 7.19	7.47, (-4 - 24), 7.87
Speech Shaped	15.33, (-2 - 31), 8.33	10.1, (0 - 25), 6.78	9.87, (-1 - 25), 6.11	7.03, (-2 - 24), 6.32
Babble	13.30, (-6 - 32), 8.01	11.27, (-1 - 29), 7.42	8.60, (-7 - 24), 8.0	7.17, (-2 - 19), 5.83

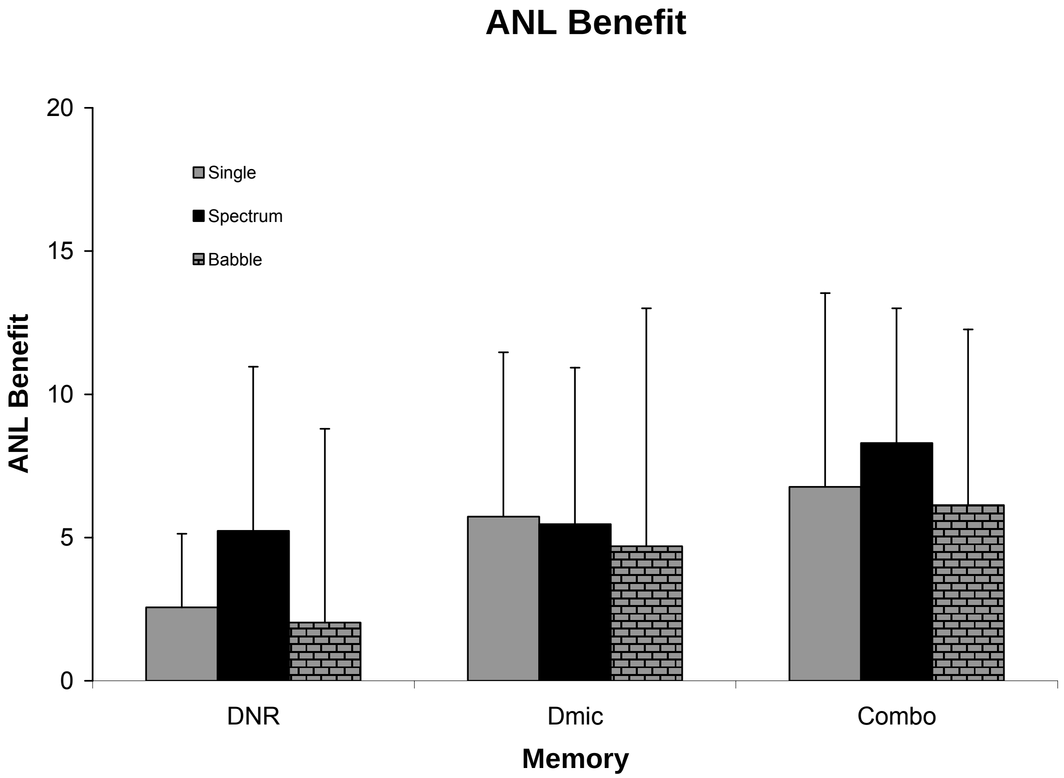

Figure 3. ANL Benefit.
Benefit scores were calculated by subtracting ANL scores obtained for each test condition from ANL baseline scores obtained during the same respective condition.

shaped noise). The analysis revealed a significant (noise reduction) technology effect [$F(2,58) = 16.599$, $p<0.01$, partial $\eta^2 = 0.364$, $\Omega = 1.000$] as well as a significant feature x noise interaction, [$F(4,116) = 2.911$, $p>0.05$, partial $\eta^2 = 0.091$, $\Omega = 0.770$] However, no significant effects were evident for noise type [$F(2,58) = 2.682$, $p>0.05$, partial $\eta^2 = 0.085$, $\Omega = 0.512$]. Paired samples t-tests were conducted to further investigate the technology main effect. All comparisons were significant controlling for familywise error rate across tests at the .05 level, using the Holm's sequential Bonferroni procedure (Table 2). These results indicate that listener's received significantly more benefit in the Combo program than in the D-Mic or DNR programs, and significantly more benefit in the D-Mic program than in the DNR program.

Paired samples t-tests were also conducted to further investigate the technology x noise interaction controlling for familywise error rate across tests at the .05 level, using the Holm's sequential Bonferroni procedure within technology condition (Table 3). Results indicated that background noise type did affect ANL benefit scores for DNR. With DNR employed, ANL benefit was significantly greater for the speech shaped noise than the single talker and the multi-talker babble. These results suggest that background noise type affected ANL benefit within the DNR memory only.

In an attempt to determine if a relationship existed between baseline ANL and the amount of ANL benefit received from technology, a correlational analysis was

Table 2. Technology t-test. Comparison from the technology data controlling for familywise error rate across the tests at the .05 level, using the Holm's sequential Bonferroni procedure within test condition.

Effect	Pair	Mean Difference	SD	*t*	*df*	Adjusted p
Technology	D-Mic, DNR	2.02	4.25	2.61	29	<0.01
	D-Mic, Combo	-1.77	2.84	-3.41	29	<0.01
	DNR, Combo	-3.79	3.59	-5.78	29	<0.01

Table 3. Technology x Noise t-test. Comparison from the technology x noise interaction data controlling for familywise error rate across the tests at the .05 level, using the Holm's sequential Bonferroni procedure within test condition.

Technology	Noise Pair	Mean Difference	SD	*t*	*df*	Adjusted p
D-Mic	Single, Speech Shaped	0.267	5.66	2.58	29	>0.01
	Single, Babble	1.03	5.97	0.95	29	>0.01
	Speech Shaped, Babble	0.767	6.1	0.67	29	>0.01
DNR	Single, Speech Shaped	-2.67	4.84	-3.02	29	<0.01*
	Single, Babble	0.53	5.31	0.55	29	>0.01
	Speech Shaped, Babble	3.2	5.81	3.02	29	<0.01*
Combo	Single, Speech Shaped	-1.53	6.23	-1.35	29	>0.01
	Single, Babble	0.63	5.86	0.59	29	>0.01
	Speech Shaped, Babble	2.17	5.46	2.17	29	>0.01

performed using mean ANL scores for each noise type and for each technology. A correlational analysis was performed with these mean data, as well as with the DNR-Speech Shaped condition, given the technology x noise interaction previously noted. Results revealed a significant correlation between ANLs measured without noise (baseline) and ANLs measured with each respective noise reduction technology (D-Mic, r = .508; DNR, r = .556; Combo, r = .592; and DNR Speech Shaped, r = .524; P[2-tailed] = < .01). These results suggest that listeners with larger (worse) baseline ANLs will receive more benefit from noise reduction technologies than listeners with smaller (better) baseline ANLs. Further, the strength of the correlation increases from DNR to D-Mic and from D-Mic to Combo, with baseline ANL most strongly correlated to the Combo condition (Figure 4).

Subjective Procedure

Rankings

Each participant was asked to rank their satisfaction with each hearing aid memory (1 = best, 3= worst) at levels corresponding to baseline values for the three background noises. Ranking data were summarized in several different ways. First, the number of times each technology was preferred (ranking of 1) was calculated for each noise condition (Figure 5). As there were 30 participants, the maximum number of “best” rankings a technology could receive would be 30 while the minimum number of “best” rankings a technology could receive would be 0. Three one-sample chi-square tests were conducted to assess the effect of noise reduction technology on preference for the three background noises.

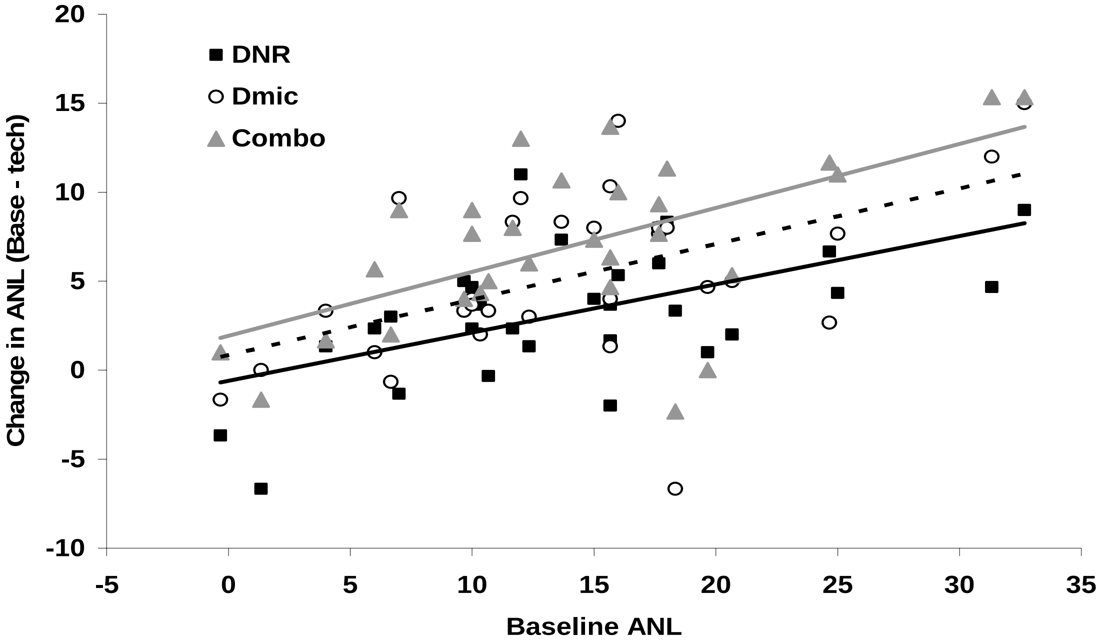

Figure 4. Benefit Correlation.
The correlation between the baseline ANL and the improvement in ANL with each noise reduction technology for the 30 participants.

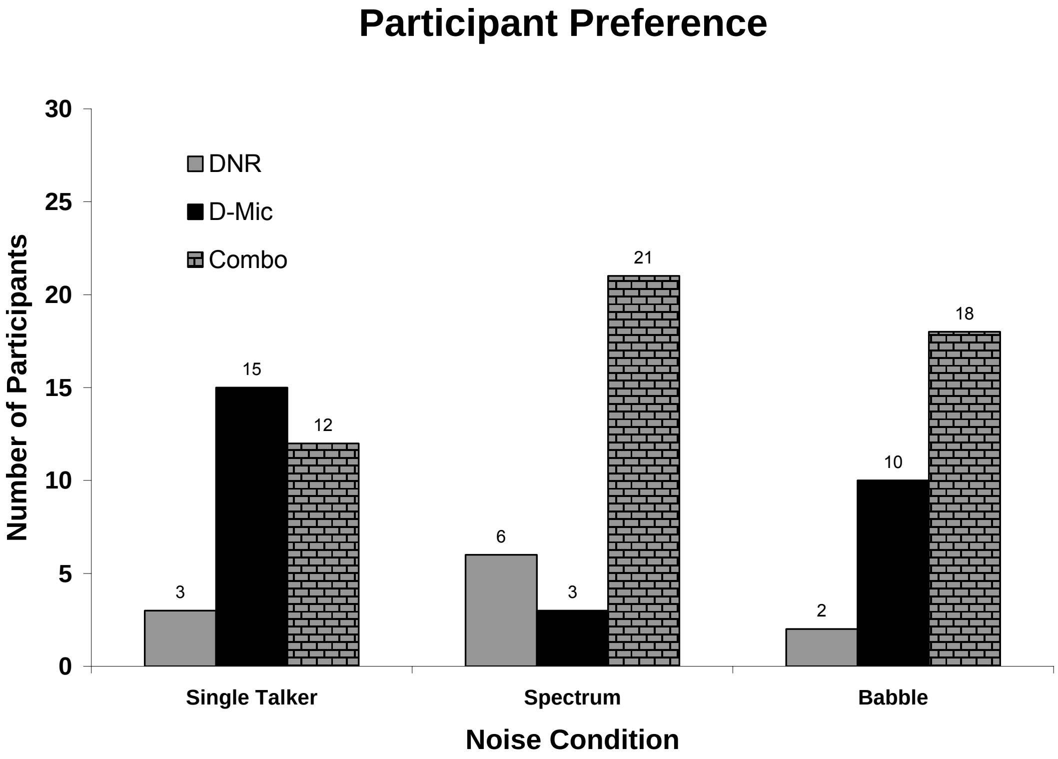

Figure 5. Participant Preference.
The number of times each technology was preferred (ranking of 1) was calculated for each noise condition. (0 to 30 = worst to best).

The results of the test were significant, indicating that for each noise, listeners preferred at least one memory greater than the hypothesized proportion of .33. The results were as follows for single talker: χ^2 (2, N = 30) = 7.80, $p < 0.05$; for speech shaped: χ^2 (2, N = 30) = 18.60, $p < 0.05$; and for babble: χ^2 (2, N = 30) = 12.80, $p < 0.05$. Follow up testing indicated that, within the single noise condition, the proportion of listeners preferring D-Mic did not significantly differ from the proportion preferring Combo, χ^2 (1, N = 28) = .333, $p > 0.05$; however, both D-Mic and Combo (respectively) were preferred significantly more than DNR, χ^2 (1, N = 12) = 8.00, $p < 0.05$; χ^2 (1, N = 15) = 5.40, $p < 0.05$. Within the speech shaped noise condition, the proportion of listeners preferring Combo was significantly greater than both D-Mic and DNR (respectively), χ^2 (1, N = 24) = 13.5, $p < 0.05$; χ^2 (1, N = 27) = 8.33, $p < 0.05$, while the proportion of listeners preferring D-Mic and DNR were not significantly different, χ^2 (1, N = 9) = 1.00, $p > 0.05$. Within the babble noise condition, the proportion of listeners preferring D-Mic did not significantly differ from the proportion preferring Combo, χ^2 (1, N = 28) = 2.29, $p > 0.05$; however, both D-Mic and Combo (respectively) were preferred significantly more than DNR, χ^2 (1, N = 12) = 5.33, $p < 0.05$; χ^2 (1, N = 20) = 12.80, $p < 0.05$. These results suggested that listeners preferred both D-Mic and Combo for background noise containing speech, and preferred Combo for non-speech-like background noise.

Second, ranking values for each technology were averaged across the 30 participants for each background noise condition (Figure 6). As a result, an average ranking of 1 would indicate that all 30 participants assigned a ranking of 1 to the technology within a given background noise whereas an average ranking of 3 would indicate that all 30 participants assigned a ranking of 3 to the technology with a given background noise condition. Similar to the preference rankings, the average rankings revealed that for both the single talker and babble noise conditions, no clear winner emerged between D-Mic and Combo, with both memories receiving better average ranks than DNR. However, for the speech shaped noise condition, Combo received a much better average rank compared to both D-Mic and DNR. These ranking values were in good agreement with the chi-square results on the preference data and support listener preference for D-Mic and Combo memories for speech-like background noise, and Combo for non-speech-like background noise.

Overall Preference

At the completion of testing, each participant was asked to indicate their overall preferred memory (Figure 7). A one-sample chi-square test was conducted to assess overall preference of memory for the three background noises. The results of the test were significant, χ^2 (2, N = 30) = 8.60, $p < 0.05$. The proportion of listeners that preferred Combo (<u>P</u> = .53) was greater than the hypothesized proportion of .33, whereas, the proportion of listeners that preferred DNR (<u>P</u> = .10) was less than the hypothesized portion of .33. The proportion of listeners that preferred D-Mic (<u>P</u> =.36) did not differ from the hypothesized portion of .33. Follow-up testing indicated that the proportion of listeners preferring Combo did

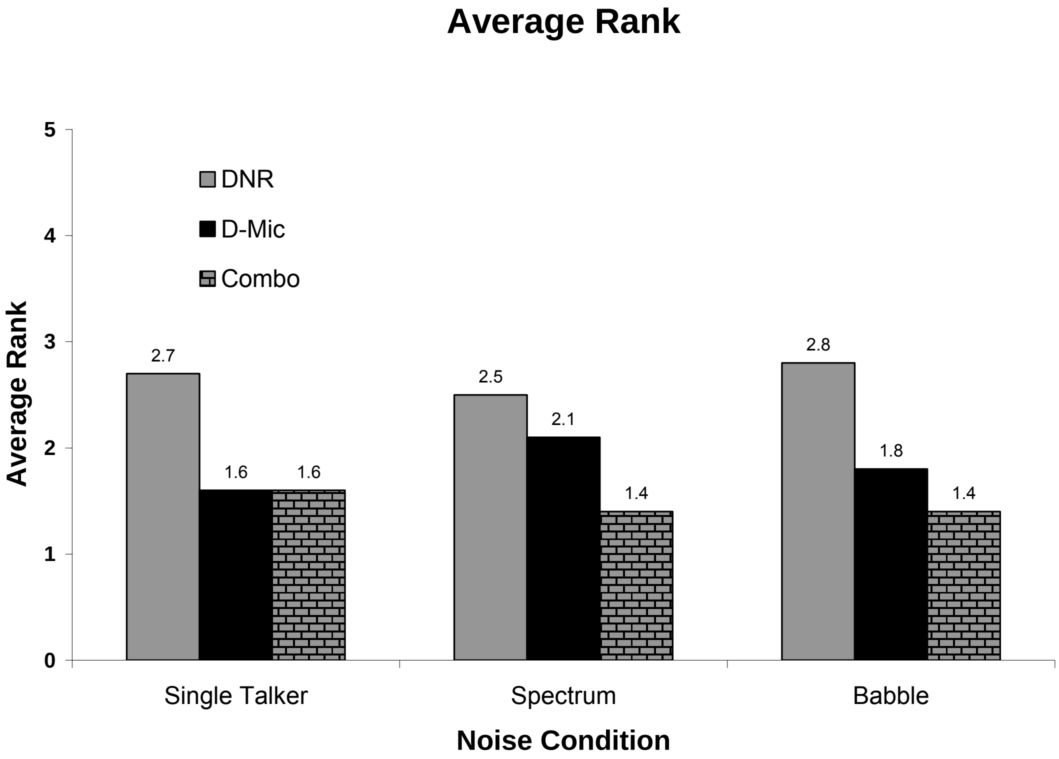

Figure 6. Average Rank.
For each technology, the average rank was calculated by obtaining the average rank per condition (technology x noise). Lower rankings = better ranking.

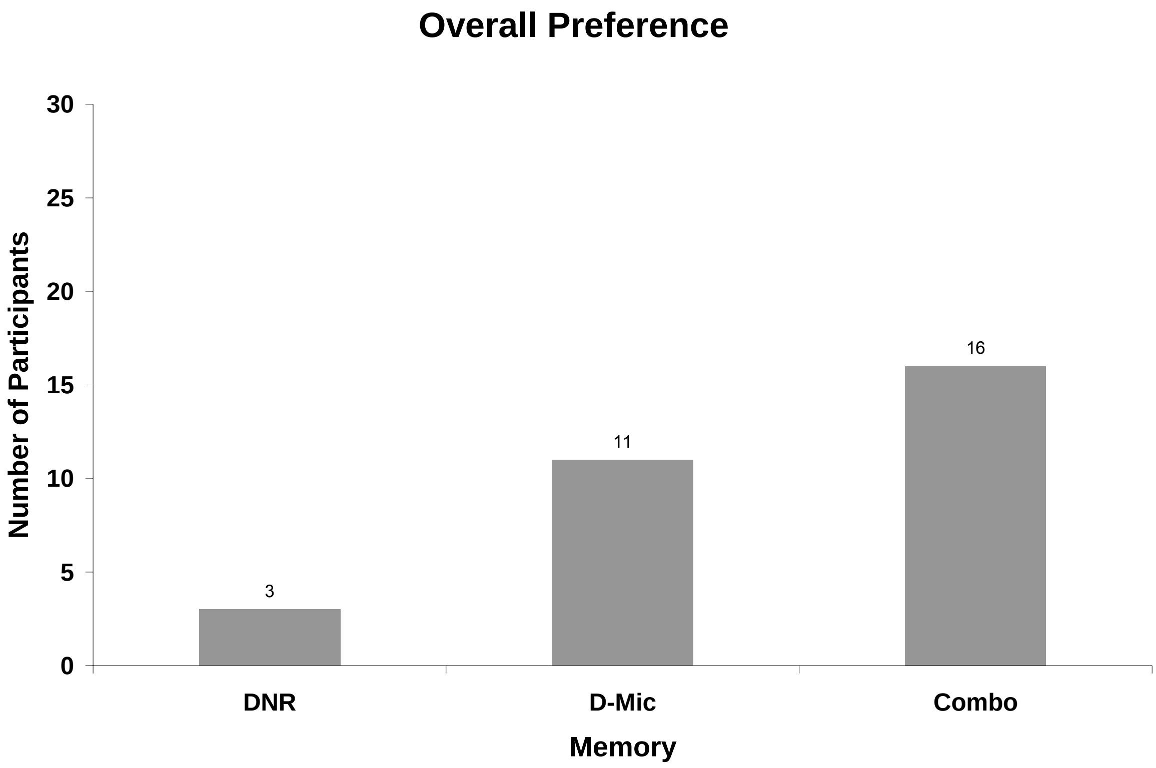

Figure 7. Overall Preference.
The overall preference was calculated by having each participant indicate which memory they preferred overall at the completion of testing.

not significantly differ from the proportion of listeners preferring D-Mic, χ^2 (1, N = 28) = .926, $p > 0.05$; however, the proportion of listeners preferring Combo and D-Mic (respectively) were significantly greater than those preferring DNR, χ^2 (1, N = 19) = 8.895, $p < 0.05$; χ^2 (1, N = 14) = 4.571, $p < 0.05$. All subjective data (Table 4) appear to correspond to ANL benefit scores.

Table 4. ANL Benefit, Rankings and Overall Preference Scores. Collapsed across noise type, the mean ANL benefit; average rank; preference rank; and overall preference were calculated for the 30 participants for each technology.

	DNR	D-Mic	Combo
ANL Benefit (dB)	3.2	5.3	7.1
Average Rank	2.6	1.8	1.4
Preference Rank	3.6	9.4	17
Overall	3	11	16

V. DISCUSSION

ANL Procedure

The goal of the present study was to determine if acceptance of noise is affected when using noise reduction technology in hearing aids in the presence of different types of background noise, as measured by ANL. Listeners yielded lower (improved) ANL scores relative to baseline when using noise reduction technologies. This ANL benefit was evident with digital noise reduction technology, directional microphone technology as well as the combination of the two technologies. Furthermore, the amount of ANL benefit differed with the respective technologies, with benefit increasing significantly from DNR to D-Mic to Combo.

Directionality and ANL

Results from this study revealed some difference in ANL benefit relative to previous studies investigating ANL and directionality. In comparing the present data to that of Freyaldenhoven et al., (2005), the mean ANL benefit was examined for the babble noise only. Those data revealed an ANL benefit of 4.7 dB with D-Mic, which compared to the 3.5 dB benefit reported by Freyaldenhoven et al., (2005), revealed an added benefit of 1.2 dB. Because the present data revealed no significant difference in ANL benefit scores between noise types, comparing the present data collapsed across noise types for the directional microphone program also provides an accurate comparison. Collapsed across noise type, the mean ANL benefit is 5.3 dB, which, compared to the Freyaldenhoven et al., (2005) data, yields an added benefit of 1.8 dB. As Freyaldenhoven and colleagues did not control for factors known to affect directional benefit such as hearing aid style, type of directional microphone, vent size or compression, the difference seen in the present study may be attributed to those factors. However, the variability noted with directional microphones in the presence of babble in the present study (-8 to 16) was similar to that reported by Freyaldenhoven (-4 to 12), suggesting that even if factors known to affect directionality are controlled for, individuals yield large variability in the amount of ANL benefit received with D-Mic technology. It should be noted that while a large range in ANL benefit was observed with D-Mic in the presence of speech babble, only 13% of participants received less benefit with D-Mic compared to baseline ANL scores. Further, 77% of participants received some benefit (> 0 dB), while 10% of participants' ANL scores remained at baseline.

Previous research has indicated that ANL values are not affected by the type of background noise used, with the exception of music (Nabelek et al., 1991); however, the effect of background noise type on ANL benefit with directionality had not been examined to date. Prior to testing, the frequency response of each background noise used in the present study was visually examined and deemed to be spectrally different from one another. Despite the difference in frequency response, no significant difference between the noises was observed in D-Mic ANL scores relative to baseline ANL scores. This lack of difference could be attributed to the noises not being different enough from one another to yield a difference in ANL score. Another explanation may lie in measurement tool used to assess “directional benefit.” Previous research investigating directionality, specifically directionality as a function of frequency, did so using objective measures such as speech intelligibility (Ricketts, Henry & Hornsby, 2005). Because previous research has suggested ANL is not correlated to objective measures (Nabelek et al., 1991; Freyaldenhoven et al., 2006; Mueller et al., 2006), perhaps no difference was seen in the amount of ANL benefit because listeners were asked to perform a task seemingly unrelated to speech intelligibility. Therefore, a direct comparison should not be made between ANL benefit scores and scores of “directional benefit” obtained with speech intelligibility tasks. Further, while these data are in good agreement with previous data and suggest that D-Mic provides an average of 5.3 dB of ANL improvement; clinicians should be warned that considerable variability exists from patient to patient.

Digital Noise Reduction and ANL

The present data were also compared to data observed by Mueller et al., (2006). Collapsing the present data across noise type for the digital noise reduction program yielded a mean ANL benefit of 3.3 dB, which is 0.9 dB lower than the 4.2 dB benefit reported by Mueller et al., (2006). The DNR program for speech shaped noise alone yielded an ANL benefit of 5.2 dB. Despite the methodological differences used in the two studies, similar benefit scores were obtained for DNR in the presence of speech shaped noise. These results suggest that DNR, as it was similarly implemented in the two studies, can improve an individual’s ANL when listening to both continuous and discontinuous speech in the presence of continuous noise. While these results reinforce the suggestion that DNR can result in improved ease of listening for speech-in-noise, it should be noted that the amount of ANL benefit will largely depend on the type of background noise present.

The mean ANL benefit across noise types for DNR was nearly 2 dB lower (worse) than that for speech shaped noise alone. This difference in ANL benefit is due to the significant difference noted in ANL benefit scores for speech shaped noise relative to either single talker or speech babble. As DNR technology differentially amplifies speech and noise based on their physical characteristics and temporal differences, it is not surprising that significant differences were observed in ANL benefit among “speech like” and “non-speech like” background noises. These data also reinforce findings of Mueller and Ricketts (2005), who reported DNR to be more effective for steady-state noises than noises containing speech.

Directionality + Digital Noise Reduction and ANL

Previous research on noise reduction technology and ANL measures has focused on investigating D-Mic and DNR independently. What remained unclear was how the combination of technologies affected ANL. The current ANL benefit data revealed listeners’ ANL scores to be significantly better (lower) using the combination of technologies than either D-Mic or DNR alone, suggesting an additive benefit. Previous studies have revealed D-Mic to positively affect intelligibility, DNR to make no impact either positive or negative, and the combination of the technologies to yield results similar to those seen by D-Mic (Ricketts & Hornsby, 2005; Walden et al., 2000), thereby suggesting no additive benefit. While no difference in intelligibility was reported for DNR, both studies revealed a listener preference for DNR over D-Mic. And, while previous benefit studies have used objective intelligibility tasks as their measurement tool for benefit, it appears that whatever factor listeners used in assessing their preference for DNR in previous "objective benefit" studies was also a factor in the assessment of their own acceptance of noise.

Interestingly, the correlational data correspond well with the ANL benefit data in that the DNR yields both the smallest benefit score and the weakest correlation, while Combo yields the largest benefit score and the strongest correlation. These data therefore suggest that individuals with larger baseline ANLs will receive greater ANL benefit from the noise reduction technologies under study than those individuals with smaller baseline ANLs. Further, the amount of benefit is correlated to the specific noise reduction technology used, with Combo clearly yielding the best opportunity for acceptance of noise. As such, according to the regression analysis performed by Nabelek et al., (2006), an individual with a high unaided ANL could benefit greatly from being fit with a Combo of technology, greatly increasing their probability of success with hearing aids.

Subjective Procedure

Although the present study revealed results comparable to previous research in that ANL scores were significantly lower (better) with both D-Mic and DNR relative to baseline, what remained unclear was how this improvement would affect listener preference. Subjective preference data revealed that noise reduction technology did affect listener preference. In terms of preference data and average rankings, listeners revealed the ability to detect some difference between the technologies under investigation. While a clear winner did not emerge between D-Mic and Combo in either background noise containing speech-like noise, it is evident that listeners preferred both D-Mic and Combo relative to DNR in these situations, suggesting that listeners were able to detect a difference between the memories with directional microphones (D-Mic and Combo) and the memory without directional microphones (DNR) in the presence of speech-like noise. Further, it is also evident that listeners preferred Combo for non-speech like noise relative to either D-Mic or DNR, suggesting some additive benefit of D-Mic and DNR in the presence of non-speech like noise. These data reflect the ANL benefit trends in that listeners preferred memories that provided the most acceptance of background noise within a given noise condition.

The overall preference data follow the same trend as the seen in the aforementioned subjective rankings data as well as seen in the ANL benefit scores in that listeners preferred D-Mic and Combo significantly more than DNR. Overall, in reviewing the preference data along with the ANL benefit data, it is evident that improving an ANL with hearing aid technology is noticeable to listeners, at least when examined in a laboratory setting. These results suggest that listeners prefer conditions in which they are able to accept more noise relative to listening conditions in which they accept less noise. As such, the combination of technologies appears to be an effective method of managing background noise that is both quantifiably and qualitatively noticed by listeners.

VI. CONCLUSION

The primary purpose of the present study was to determine if noise reduction technology affected acceptance of noise in the presence of different types of background noise. Results suggest that noise reduction technologies improve ANL in the presence of single talker, speech shaped, and babble noise. Results further suggest that the amount of improvement depends upon an individual's baseline ANL score, with the larger (worse) scores receiving more benefit from technology than smaller (better) baseline scores. In addition, the type of noise reduction technology employed as well as the type of background noise present affect the amount of benefit received, with Combo and D-Mic providing more benefit than DNR in the presence of speech-like background noise, and Combo providing more benefit than DNR and D-Mic in the presence of non-speech like background noise.

Also of interest was to determine if noise reduction technology affected subjective preference scores. Results suggest that ANL benefit impacts subjective preference insomuch as listeners prefer the noise reduction technologies that yielded the most improvement in terms of noise acceptance within a given listening condition.

It should be noted that while these data are promising in terms of improving a listener's acceptance of noise and perhaps their success with amplification, further investigation is warranted regarding how this ANL benefit translates into "real world success." As these data were obtained in a laboratory, under ideal conditions, it is unclear if the findings will generalize to real-world success. In addition, these results can only be attributed to the testing set-up and hearing aid parameters implemented in the present study. Real world settings rarely present speech at 0-degree azimuth only and noise at 180-degree azimuth only, as was investigated in the present study. As such, future research should investigate the effects of the technologies in more diffuse listening situations and perhaps with adaptive directional microphones.

Again, while these data are promising in terms of improving one's acceptance of noise, the ultimate goal of such research is to translate into helping individuals with high ANLs become more successful hearing aid users. As such, a field-based investigation should explore whether an improvement in ANL, as provided by noise reduction technologies, produces a change in hearing aid use patterns. Also, in addition to a field-based investigation employing the technology explored in the present research, additional ways to improve ANL scores should be explored. For example, FM systems; which improve signal to noise ratio, decrease distance between the sound source and listener, and overcome reverberation; should be investigated in terms of their ability to affect ANL independently of noise reduction technologies, as well as in combination with noise reduction technologies, as there may be an additive effect. In addition, auditory training as well as the role of the visual system may warrant investigation regarding their ability to affect an individual's ability to accept noise.

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APPENDICES

Appendix 1 (ANL Instructions provided to each participant prior to testing)

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. Handheld buttons will allow you to make adjustments. First, turn the loudness up until it is too loud and then down until it is too soft. Finally, select the loudness level 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 the same 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 or "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 time while following the story.

Appendix 2 (Subjective rating instructions provided to each participant prior to testing)

You will be asked to listen to each memory under each of 3 noise conditions. For each noise condition, please rank each memory 1-3 (1 being the best, 3 being the worst) according to your preference for that particular memory/ noise condition.

Noise Condition 1
Memory 1 ______

Memory 2 ______

Memory 3 ______

Noise Condition 2
Memory 1 ______

Memory 2 ______

Memory 3 ______

Noise Condition 3
Memory 1 ______

Memory 2 ______

Memory 3 ______

VITA

Kristy Jones Lowery was born in Gulfport, MS on January 22, 1979. She was raised in Saucier, MS and went to grade school at Saucier Elementary, junior high school at North Gulfport and graduated from Harrison Central High School in 1997. From there, she went to Millsaps College in 1997 and received a B.A. in psychology in 2000. Kristy received a M.A. in audiology from the University of Tennessee, Knoxville in 2005. From there, she earned her certificate of clinical competence and state license to practice audiology in 2007.

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