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Real-world benefit from directional microphone hearing aids

David Gnewikow, PhD;[1*] Todd Ricketts, PhD;[2] Gene W. Bratt, PhD;[3] Laura C. Mutchler, AuD[4]
[1]Advanced Hearing Solutions, Mount Juliet, TN; [2]Vanderbilt Bill Wilkerson Center for Otolaryngology and Communication Sciences, Vanderbilt University School of Medicine, Nashville, TN; [3]Department of Veterans Affairs Tennessee Valley Healthcare System, Nashville, TN; [4]Baptist Memorial Hospital, Memphis, TN

Abstract—This article summarizes data from a 3-year, double-blinded study of directional hearing aid benefit. Ninety-four subjects in three hearing loss groups, all previous users of omnidirectional output-compression hearing aids, completed all aspects of the study. Participants were fit with new hearing aids for 1 month in a directional mode and 1 month in an omnidirectional mode. Following 1 month of use, subjects completed a number of objective and subjective measures of hearing aid outcome. Objective and subjective data were analyzed across hearing aid and hearing loss conditions. Subjects in all hearing loss groups exhibited better performance in the directional conditions for objective speech-in-noise measures; however, subjective data did not indicate a clear advantage for directional amplification. Results and clinical implications are discussed.

Clinical Trial Registration: ClinicalTrials.gov; Real-World Benefit from Directional Hearing Aids, NCT00438334; http://www.clinicaltrials.gov/ct2/show/NCT004383341/.

Key words: benefit, directional microphones, hearing, hearing aids, hearing loss, noise, objective benefit, signal-to-noise ratio, speech understanding, subjective benefit.

INTRODUCTION

Sensorineural hearing loss (SNHL) is a disability affecting an estimated 25 million Americans [1]. Hearing loss is one of the most common disabilities experienced by the aging veteran population. Aside from causing a loss of sensitivity to speech and other sounds, hearing loss may affect mental and social well-being, which in turn significantly affects an individual's overall quality of life [2]. The use of hearing aids, particularly in quiet environments, has been shown to not only effectively improve speech understanding over unaided listening [3–5] but also significantly improve quality of life [2].

Although hearing aids usually allow for better audibility of speech sounds, individuals with hearing impairment continue to have particular difficulty in background noise [6–10]. Background noise negatively affects the hearing aid wearer's understanding of speech, listening comfort, and overall hearing aid benefit [11–13]. One investigation indicated that 25 percent of individuals who own hearing aids but do not wear them cite poor performance in background noise as the reason for hearing aid rejection [14].

The signal-to-noise ratio (SNR) is the primary factor that affects speech understanding in noise [6,15–16]. The SNR describes the intensity differences between the signal

Abbreviations: ANOVA = analysis of variance, CST = Connected Speech Test, HINT = Hearing In Noise Test, HL = hearing level, HSD = honestly significant difference, IRB = Institutional Review Board, NAL-R = National Acoustics Laboratory-Revised, PHAB = Profile of Hearing Aid Benefit, PTA = pure tone average, SADL = Satisfaction with Amplification in Daily Life, SD = standard deviation, SII = Speech Intelligibility Index, SNHL = sensorineural hearing loss, SNR = signal-to-noise ratio, SPL = sound pressure level, SRT = speech reception threshold, VA = Department of Veterans Affairs.

*Address all correspondence to David Gnewikow, PhD; Advanced Hearing Solutions—Audiology, 1002 Pleasant Grove Place, Suite C, Mount Juliet, TN 37122; 615-758-7999; fax: 615-758-7997. Email: docg@hearlife.org**

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of interest (in any given environment) and competing stimuli. For an individual's speech intelligibility in noise to improve, the SNR must be improved. In general, omnidirectional hearing aids do not improve the SNR in comparison with the unaided ear, and in some cases, the SNR can be worsened by amplification [17–19]. Directional hearing aids incorporate multiple microphones (or microphone ports) to improve SNR based on the spatial location of the signal of interest (front hemisphere) relative to unwanted signals (usually the rear hemisphere). The SNR is improved by providing more gain for sounds arriving from frontal azimuths than for those arriving from rear azimuths. The improvement in SNR relative to omnidirectional hearing aid fittings can lead to improved speech intelligibility in noisy environments [18,20–23].

Directional Benefit and Degree of Hearing Loss

To date, most research in the area of directional hearing aids has focused on individuals with mild-to-moderate hearing impairments [10,18,23–26]. In general, the majority of this research has shown significant improvements for speech intelligibility in noise as measured by laboratory tests; however, the degree to which these data are applicable to subjects with less or more severe SNHL remains unclear. A few studies have examined directional hearing aid use with subjects with severe-to-profound SNHL. Potts et al. presented data suggesting a directional preference in a severe-to-profound SNHL subject pool fitted with power directional hearing aids.* Kühnel et al. tested 21 experienced hearing aid users with a multimicrophone power hearing aid [27]. Their results indicated a preference for the experimental aid, somewhat improved speech intelligibility, and increased satisfaction under directional conditions compared with their previous omnidirectional hearing aid. More recently, the potential for directional hearing aid benefit in 15 listeners with severe hearing loss, defined as pure tone averages (PTAs) of >65 dB, was examined at multiple SNRs for both auditory only and audiovisual presentation modes [28]. The results of this study generally support a small but significant directional advantage for listeners with severe hearing loss in a difficult listening environment both with and without the presence of visual information.

Although these studies indicate the potential for directional benefit for subjects with severe-to-profound SNHL, the database for subjects with more severe hearing impairments is limited. Furthermore, no data exist for subjects with milder losses. Individuals with normal hearing in the low frequencies and deficits in the high frequencies have not been studied independently. Thus, the need for a systematic investigation of directional benefit across various degrees of hearing loss appears warranted.

Laboratory Tests Versus Real-World Environments

The conditions under which directional hearing aids are evaluated are important to consider. Some studies have demonstrated directional advantages with experimental parameters that do not represent environments that subjects are likely to encounter in the real world, such as speech at a 0° azimuth and noise at a 180° azimuth [18,20,23,29]; correlated noise sources [17,30–32]; or speech in sound attenuating, relatively nonreverberant environments [17,23,29,33].

Ricketts evaluated the effects of multiple noise sources on directional benefit [24]. Results from this investigation indicated less directional benefit for multiple noise sources relative to the 0°/180° condition. Although significant directional benefit remained, failure to reproduce more "real-world" listening environments clearly may overestimate directional benefit. Compton-Conley et al. evaluated directional microphone hearing aid performance under several simulated noise configurations and in a live restaurant situation [34]. The single-noise-source simulations did not accurately represent the real-world performance of the hearing aids, while the simulation with seven equally spaced noise sources playing back recorded noise from the restaurant most adequately reproduced the real-world results.

Ricketts and Hornsby [35] and Ricketts [24] evaluated the effects of reverberation on directional benefit. Both investigations indicated that directional benefit decreased as reverberation increased. Failure to adequately reproduce realistic reverberation characteristics may once again result in an overprediction of directional benefit.

Noise-source correlation is another factor that must be considered in directional hearing aid research. Correlated noise occurs when identical noises are delivered simultaneously from multiple noise sources. An experiment with uncorrelated noise uses multiple noise sources with spectrally matched but temporally dissimilar (uncorrelated) signals. Cox and Bisset showed that the use of multiple correlated noise sources may result in a release from masking

*Potts L, Valente M, Voll L. Performance of a dual-microphone hearing aid with severely hearing-impaired individuals. Presented at American Academy of Audiology Annual Convention; 2000 Mar 17; Chicago, IL.

and may provide the listener with an advantage that would not be realized in uncorrelated noise [36]. Compton-Conley et al. acknowledge that the use of correlated noise sources is not typical of real-world listening environments [34]. Gnewikow reported significant differences in speech intelligibility scores for subjects tested under correlated noise and uncorrelated noise conditions, depending on the method of calibration.* Because of the summation effects of multiple correlated noise sources in free field, results from speech intelligibility in noise tests may indicate significantly better speech reception thresholds (SRTs) for correlated noise sources than for uncorrelated sources under the same conditions. Thus, the use of uncorrelated noise sources is more realistic and more reliable for testing speech intelligibility in the presence of multiple background noise sources.

Objective and Subjective Measures of Benefit

While quite a few studies have tested speech intelligibility under various directional-microphone conditions, relatively few have examined the concomitant effects on subjective benefit. Valente et al. measured hearing aid benefit with directional hearing aids [23] using the Profile of Hearing Aid Benefit (PHAB) [37]. The authors reported better PHAB scores for the directional hearing aids on the background noise and reduced cues subscales relative to normative data. The comparison with normative data, however, does not allow for a conclusion about the amount of benefit that is attributable to the directional hearing aid alone. Preves et al. investigated subjective benefit for experimental hearing aids with omnidirectional compensated directional and noncompensated directional settings [38]. A compensated directional setting increases the gain in the low frequencies to offset the low-frequency reduction that typically occurs when directional microphones are active. The noncompensated directional setting does not adjust for the low-frequency gain reduction and thus results in less low-frequency amplification. PHAB results indicated that subjects reported significantly more benefit with the compensated directional setting than with the omnidirectional setting in the reverberation and background noise subscales. The noncompensated directional and omnidirectional settings were not significantly different from one another. Walden et al. compared user-selectable directional hearing aids to subjects' own hearing aids using the PHAB and Connected Speech Test (CST) [39]. Although subjects performed better on the CST, significant differences in PHAB scores were not present between the experimental and previous aid conditions. Ricketts et al. tested 15 subjects with symmetrical sloping hearing loss using the CST and the Hearing-in-Noise Test (HINT) to assess objective benefit and the PHAB to measure subjective benefit [40]. These authors reported more benefit for the user-selectable directional/omnidirectional mode of the experimental hearing aid on the background noise subscale of the PHAB than for the omnidirectional condition. They also reported better performance on the objective measures of speech intelligibility in the directional conditions than in the omnidirectional condition. Recently, Palmer et al. evaluated subjective benefit from hearing aids implementing one of three directional settings: automatically-switching directional condition, fixed directional condition, and omnidirectional condition [41]. The authors reported no significant trend in the user preferences across the three microphone conditions.

Based on the current status of knowledge gathered in the literature on benefit from directional hearing aids, our current study was designed to provide a comprehensive understanding of directional benefit across a number of variables. First, we grouped subjects by degree of hearing loss to determine whether significant differences in directional benefit could be attributable to hearing sensitivity. Second, we used a variety of measures to assess overall hearing aid outcome, including two tests of speech intelligibility in noise, a test of subjective hearing aid benefit, a profile of hearing aid satisfaction, a use questionnaire, and a preference questionnaire. Third, to control variability among subjects due to differences between their previous hearing aids and the experimental devices, we chose subjects who were previous users of output-compression, omnidirectional hearing aids. We implemented this control as an attempt to isolate the experimental variable of directionality and to limit other influences, such as changes in hearing aid size and hearing aid processing. Fourth, our study was a double-blind design, such that neither the subject nor the person administering the various tests was aware of the experimental hearing aid settings (omnidirectional or directional). Fifth, all speech-in-noise testing was performed in a difficult "real-world" environment with multiple uncorrelated noise sources spaced about the listener and moderate reverberation times.

*Gnewikow D. Free-field and interaural noise correlation: Effects on intelligibility. Presented at American Auditory Society Scientific and Technology Meeting; 2004 Mar 7; Scottsdale, Arizona.

The overall purposes of our experiments were to determine (1) whether significant directional benefit could be obtained in a real-world listening environment, (2) the relationship between degree of hearing loss and directional benefit, and (3) whether significant differences were present in the self-reported benefit data between omnidirectional and directional conditions.

METHODS

Subjects

We recruited 105 subjects for participation in this study, 35 in each of three hearing loss groups. Subjects were assigned to the three groups according to the severity of their hearing losses. Group 1 (mild) subjects exhibited normal hearing that sloped to moderately severe SNHL with PTAs at 500, 1,000, and 2,000 Hz of <35 dB hearing level (HL) averaged between ears. Mean ± standard deviation (SD) thresholds for the mild group are shown in **Figure 1**. Group 2 (moderate) consisted of subjects with mild sloping to moderately severe SNHL with PTAs of 35 to 50 dB HL averaged between ears. Mean ± SD thresholds for the moderate group are shown in **Figure 2**. Group 3 (severe) subjects exhibited moderately severe sloping to severe-to-profound SNHL with PTAs of >50 dB HL averaged between ears. Mean ± SD thresholds for the severe group are shown in **Figure 3**. All subjects had sloping hearing loss defined as at least a 20 dB average difference between 500 Hz and 3,000 Hz. Some subjects were unable to complete all the required visits because of illness, transportation, or other personal issues; thus, the final data consisted of 32 subjects in the mild group, 33 in moderate group, and 29 in the severe group. Only the data from the subjects who completed all aspects of the study were included in the aforementioned figures and the following analyses. All subjects whose data are included herein were male service-connected veterans receiving care through the Department of Veterans Affairs (VA) Tennessee Valley Healthcare System. These data were collected under the rules and regulations set forth by the VA Tennessee Valley Healthcare System Institutional Review Board (IRB), and all recruitment and data collection were completed after receiving IRB approval.

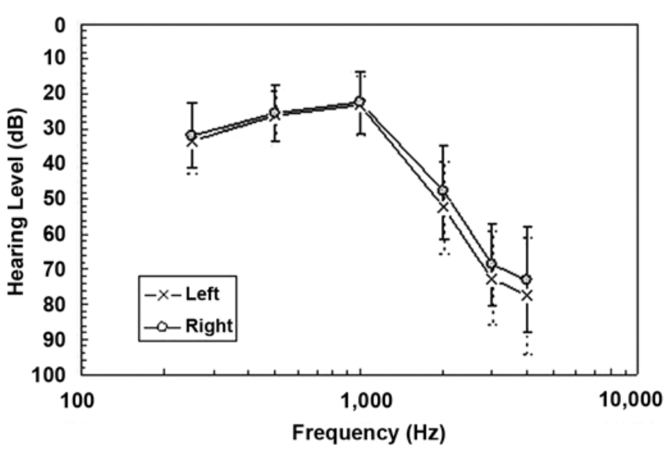

Figure 1.
Mean thresholds, mild group.

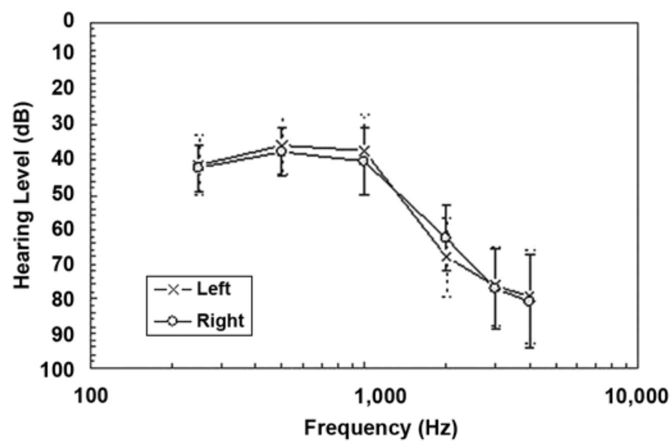

Figure 2.
Mean thresholds, moderate group.

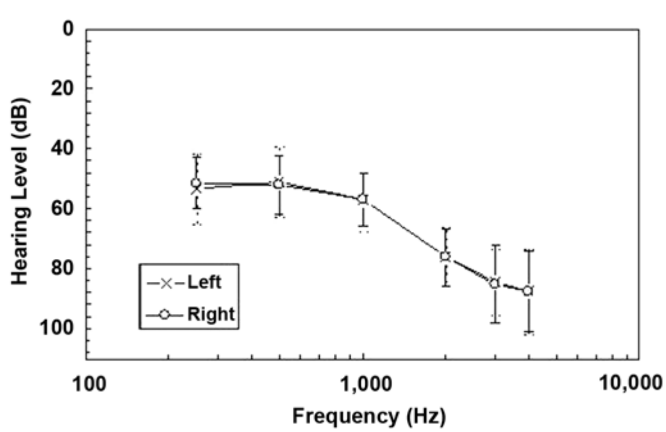

Figure 3.
Mean thresholds, severe group.

Hearing status was assessed by means of audiometric pure tone and speech recognition testing in a group of previous hearing aid users. Normal middle-ear function was verified by means of immittance measures. All subjects exhibited absence of a significant air-bone gap at any frequency (<10 dB) and normal tympanograms defined as compensated static admittance between 0.25 and 2.5 siemens measured from the positive tail with tympanometric peak pressure between –150 and +100 daPa. All subjects were service-connected veterans who were eligible for care and amplification through the VA Audiology service. All subjects were previous wearers of binaural hearing aids, with a minimum daily-usage requirement of 4 hours/day. All subjects were previous users of output-compression Phonak hearing aids (The Phonak Group, Phonak AG; Staefa, Switzerland).

Speech-In-Noise Tests

The CST and HINT were administered to all the subjects. An investigator in the room with the subject scored the test. The investigator was blinded to the experimental settings of the hearing aids to control for experimenter bias. The CST is a test of speech intelligibility for everyday speech presented at a fixed SNR [42–43]. The test consisted of 24 pairs of speech passages produced conversationally. The subject's task was to repeat all words of each test sentence. Each passage included 25 key words that were scored correct or incorrect. Subject scores from one pair of passages were averaged to obtain an intelligibility score for each experimental condition. Data from Pearsons et al. indicate that real-world SNRs in relatively noisy listening environments range from approximately +4 dB to –1 dB [44]. Consequently, the tests were administered at +3 dB SNR, which represented a relatively difficult real-world listening situation. We chose this SNR to minimize floor and ceiling effects for all subject groups, based on pilot data collected prior to the initiation of these experiments and given the steep performance-intensity function that has been reported for the CST [42].

The HINT was administered as a second test of sentence understanding in noise [45]. For this investigation, two blocks of ten sentences were used for each condition. Listeners were required to repeat sentences spoken by a male in the presence of a speech-shaped noise, which was presented at a fixed level of 65 dBA. The level of the speech stimuli was adjusted adaptively until an SRT was determined. The SRT was defined as the SNR necessary for a listener to recognize the speech materials correctly 50 percent of the time. Correct identification of each sentence was based on proper repetition of all words of the sentence, with minor exceptions. These exceptions related to the small substitutions in verb tense, and the articles "a" and "the" were allowed without scoring a sentence as incorrect [45]. The presentation level of the sentences was adjusted based on the subjects' responses (an incorrect response raised the level and a correct response lowered the level for the next sentence). The level was varied in 4 dB steps for the first 5 trials, and in 2 dB steps for the final 15 trials. The subject's SRT score was calculated as the average SNR of the final 15 trials.

Speech-in-Noise Test Environment

The arrangement of the loudspeakers for the speech-in-noise testing is shown in **Figure 4**. Both speech-in-noise tests were administered in a conference room in the Audiology Department at the Nashville campus of the VA Tennessee Valley Healthcare System. The room measured 5.05 × 4.71 × 2.60 m, with moderate reverberation (average reverberation time: 482 ms, measured for octave frequencies from 250 through 4,000 Hz under experimental conditions with two people in the room).

Each subject was seated in the center of the room with an eight-loudspeaker configuration for the presentation of the speech and noise stimuli. Speech was presented from a point-source loudspeaker (Tannoy System 600, fused-concentric driver; Tannoy; Ontario, Canada) at 0° azimuth. Uncorrelated noise was delivered from the seven bipolar loudspeakers (BP-2X; Definitive Technology;

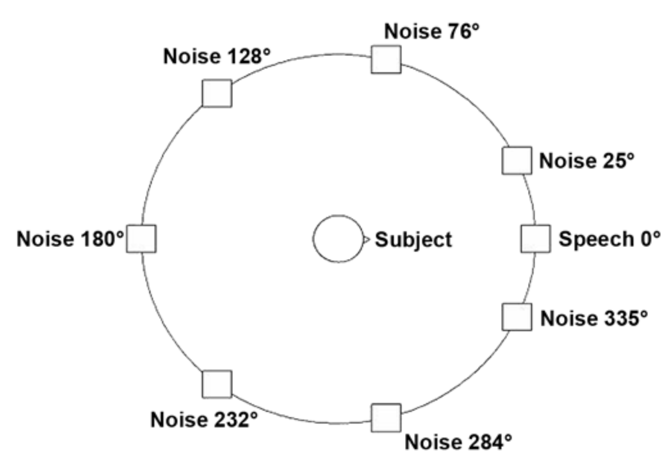

Figure 4.
Loudspeaker arrangement for Hearing in Noise Test and Connected Speech Test.

Owings Mills, Maryland) spaced equally about the listener (approximately 25°, 76°, 128°, 180°, 232°, 284°, and 335°). The use of bipolar loudspeakers allowed for a more diffuse source position compared with standard, front-firing loudspeakers. All loudspeakers were equidistant (1.5 m) from the subject's head. During the experimental sessions, speech and noise levels were controlled by the investigator in the room using a Pentium IV (Intel; Santa Clara, California) class computer and an eight-channel level controller (VCM-88, Ashly Audio; Webster, New York).

Prior to subject testing, calibration was performed. A sound level meter (Model 800B, Larson Davis, Inc; Provo, Utah) was placed on a tripod in the center of the room with the microphone at the position of the subject's head. The output of each of the seven individual noise loudspeakers was independently calibrated to 50 dBA ± 0.5 dB for identical speech noises. Any adjustments to the output level of the noise loudspeakers were achieved by adjustment of the gain on the amplifier for that particular channel. Thus, the level of each loudspeaker was adjusted independently until the same output was obtained for all seven loudspeakers. Second, the output of the speech loudspeaker was then calibrated to 65 dBA ± 1 dBA with a sample of the speech noise derived to have the same long-term average spectrum as the HINT sentences. Next, all seven noise loudspeakers were turned on and the overall level was calibrated to 65 dBA ± 0.5 dB. Finally, for the CST materials, the speech loudspeaker was calibrated to 68 dBA ± 0.5 dB with a speech noise derived to have the same long-term average spectrum as the CST passages. The calibration of the noise loudspeakers was not varied for the CST passages.

Subjective Measures

PHAB

The investigator who administered the subjective measures was masked to the experimental settings of the hearing aids. All subjects completed the PHAB questionnaire [37,46–47] for each condition: unaided, previous aid, experimental directional, and experimental omnidirectional. The PHAB is a 66-item inventory that was developed for research usage to generate a measure of hearing aid benefit. Subjects completed the 66 items once for unaided listening and once for each aided condition. The test instrument was scored based on the benefit provided for the aided versus unaided conditions.

SADL

All subjects completed the Satisfaction with Amplification in Daily Life (SADL) questionnaire [48] for each of the three aided conditions. The SADL was designed to quantify satisfaction with hearing aids. This scale consists of 15 items in 4 subscales: positive effects of amplification, service and costs, negative features, and personal image. Subjects responded to questions about their general opinions of wearing hearing aids. For our study, one question on the service and costs subscale (Item 14: Does the cost of the hearing aids seem reasonable to you?) was omitted, because the subjects did not pay for the hearing aids.

User-Preference Questionnaire

At the conclusion of a subject's involvement in the study, a hearing aid user-preference questionnaire was administered (**Appendix**, available online only). Subjects were asked to rate their preferences for either their old hearing aids, the experimental hearing aids in setting one, the experimental hearing aids in setting two, or no preference. Subjects rated their preferences for quiet environments, noisy environments, and overall.

Subject Visits and Data Collection

All subjects participated in approximately 8 to 10 hours of testing over the course of four visits. At the first visit, subjects received a hearing test, unaided speech-in-noise measures, and aided speech understanding in noise with their current hearing aids. Additionally, earmold impressions were obtained for the experimental hearing aids. At the second visit, subjects completed the first set of subjective measures for the unaided and current (own) hearing aid conditions. In the first of two experimental settings (randomly selected between directional/omnidirectional and omnidirectional only), subjects were fit bilaterally with digitally programmable user-selectable directional/omnidirectional hearing aids which they used for approximately 1 month before returning for the next test session. At the third visit, subjects again completed the entire test battery, including the subjective questionnaires and the speech-in-noise tests, for the experimental hearing aids worn during the last month. The experimental hearing aids were then programmed for the other condition (directional/omnidirectional or omnidirectional only). At the fourth and final visit, subjects completed the entire test battery for the final hearing aid condition. Additionally, at the final visit, subjects completed a user-preference questionnaire (**Appendix**, available online only).

Hearing Aid Fitting Protocol

For the experimental hearing aid conditions, we fit all patients bilaterally with programmable hearing aids with a dual-microphone directional system. The hearing aids had no noise-reduction features apart from the directional microphones. The experimental hearing aids had three user-selectable programs, accessible via remote control. We determined hearing aid gain with the National Acoustics Laboratory-Revised (NAL-R) prescriptive targets and verified with real-ear (Fonix 6500, Frye Electronics, Inc; Tigard, Oregon) measurements. In the old aid and both experimental hearing aid conditions, frequency-gain parameters were adjusted in each ear independently so that the measured real-ear aided response matched the target response as closely as possible for octave frequencies from 500 to 4,000 Hz for both omnidirectional and directional modes at a 45° azimuth from center (per the Fonix 6500 protocol). The processing strategy of the experimental hearing aids was set as output compression to match each subject's previous hearing aids. Targets were matched for a 65 dB sound pressure level (SPL) composite-noise input. We obtained a real-ear saturation response with a 90 dB SPL broadband input to ensure that high-level stimuli did not exceed listener discomfort levels and adjusted the hearing aid output accordingly. All experimental hearing aids had a variable venting system. We varied the venting to maximize patient comfort and achieve the best matches to real-ear targets. In general, vents were significantly more open in the mild hearing loss group and largely closed in the severe group.

To maintain a double-blind experiment, one investigator performed the hearing aid programming, fitting, and real-ear measurements and recorded how the hearing aid was set (omnidirectional or directional) for each visit. This investigator kept these data until the subject completed all aspects of the study. Furthermore, the investigator who programmed and fit the hearing aids was not involved in further data collection with that subject.

Because all subjects were previous users of binaural amplification, a brief orientation to the use of the experimental hearing aids was deemed sufficient. Subjects were issued a remote control with a volume-control and three program buttons. The first program was set with the default setting (directional or omnidirectional). To ensure subject safety, we included an omnidirectional program in the second program across both conditions; however, subjects were instructed to use the second program only for situations in which it was necessary to hear sounds from all angles equally (e.g., crossing the street in traffic). The third program on the remote control was set to mute so that subjects could use only the first two programs. Subjects were given identical instructions for both settings (omnidirectional and directional), and the investigator who gave the instructions did not know which setting the subject's hearing aids were using. Subjects were told that the hearing aids were likely to work best in noise if they could position themselves with the signal of interest in front of them and the interfering noise behind. Subjects were instructed on cleaning, care, battery usage, and volume-control adjustment. Subjects were asked to wear the experimental hearing aids as much as possible during waking hours, a minimum of 6 hours a day. We asked subjects to log their daily hearing aid use on a sheet to verify that they met the 6 hour a day criterion. Additionally, subjects recorded how much time each day was spent in each of the two programs.

RESULTS

Probe-Microphone Data

The real-ear data shown for each experimental condition are averaged across both right and left ears. **Figure 5** shows mean real-ear SPLs as measured with a Fonix 6500-CX probe-microphone system for the mild hearing loss group. Hearing aid data for the three aided conditions are shown relative to an NAL-R target for a 65 dB

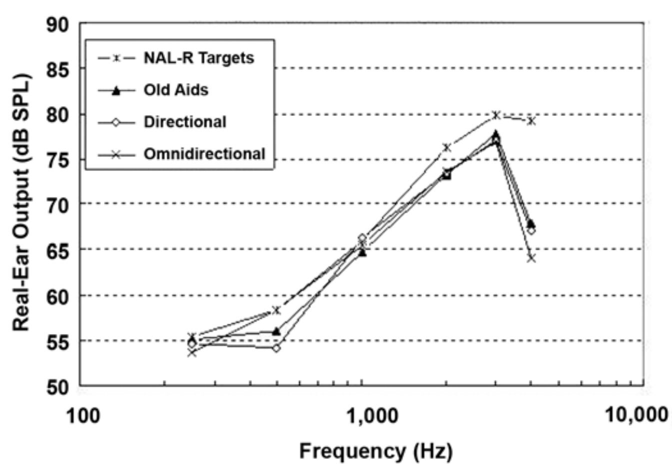

Figure 5.
Mild group, hearing aid frequency-response characteristics. NAL-R = National Acoustics Laboratory-Revised, SPL = sound pressure level.

SPL composite-noise input. As previously stated, response characteristics of the experimental hearing aids were set to the best possible matches to the NAL-R target in both omnidirectional and directional conditions. The mean frequency responses for the three conditions are similar; however, the experimental omnidirectional gain more closely matched the prescriptive target than the old aid and directional conditions.

Real-ear frequency-gain characteristics for the moderate hearing loss group are shown in **Figure 6**. The pattern of the matches to target is similar to that of the mild group, with the experimental omnidirectional condition matching target better than the old aid and directional conditions at 500 Hz. Furthermore, all the hearing aid conditions had more variance from target at 3 to 4 kHz, presumably because of the severity of the losses and limits of gain due to feedback.

Average real-ear data from the severe group are shown in **Figure 7**. These data show a different pattern from the mild and moderate groups. Once again, the real-ear target is best matched with the omnidirectional condition; however, both the old aid and directional conditions fall below the target and omnidirectional responses for this group. Because of the severity of the hearing losses in this group and the inherent reduction in gain in a directional-microphone mode with these hearing aids, experimenters generally were not able to increase the gain to match that of the omnidirectional response. As with the moderate group, we noted a divergence from target at the higher frequencies due to the limits of amplification with feedback and receiver characteristics.

The Speech Intelligibility Index (SII) is a computation that quantifies the amount of intelligible information in any given acoustic environment for an average listener. Although a variety of variables can be included in the SII calculation, the formula is primarily based on the level and frequency content of the signal, the HLs of the subject, the amount of amplification provided, and the level and type of competing noise. We performed SII calculations on the average probe-microphone data to determine whether significant differences in audibility were present between experimental conditions. Those data are shown in the **Table**. The differences in calculated SII were minimal within groups, with the largest within-group SII difference being 0.021. Given the small differences in measured SII, differences in audibility did not likely contribute significantly to the overall pattern of results.

Speech-In-Noise Testing

HINT

Results from the HINT are shown in **Figure 8**. The HINT score quantifies the average SNR for 50 percent identification of sentence materials; thus, a lower score indicates of better performance. An analysis of variance (ANOVA) yielded a significant main effect of hearing loss group, $F_{2,6} = 35.7$, $p < 0.001$. As would be expected, the

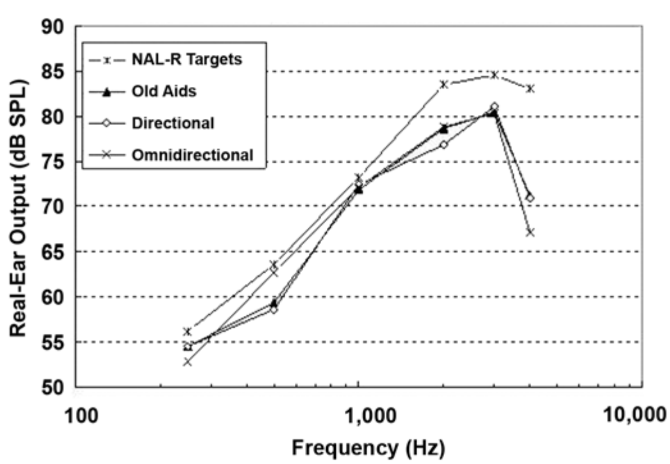

Figure 6.
Moderate group, hearing aid frequency-response characteristics. NAL-R = National Acoustics Laboratory-Revised, SPL = sound pressure level.

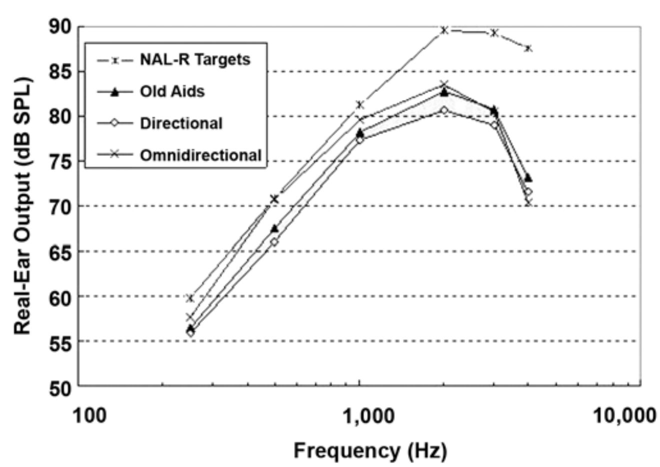

Figure 7.
Severe group, hearing aid frequency-response characteristics. NAL-R = National Acoustics Laboratory-Revised, SPL = sound pressure level.

mild group showed the best HINT scores and the severe group had the worst performance. We used the Tukey honestly significant difference (HSD) test to follow up on the effect of hearing loss group. This analysis indicated that the differences between the mild, moderate, and severe groups were all statistically significant ($p < 0.005$).

Similarly, we found a significant main effect of hearing aid condition, $F_{3,6} = 59.5$, $p < 0.001$. We used the Tukey HSD test to follow up the significant main effect of hearing aid condition. This analysis indicated that all four hearing aid conditions differed significantly ($p < 0.005$). Thus, the HINT data indicated that performance was best across hearing loss groups in the directional condition followed by the experimental aid in the omnidirectional setting and then the old aid condition. As expected, across groups, the poorest performance was in the unaided condition.

No significant interaction effects were found, indicating that the effect of the hearing aid conditions was similar across the three hearing loss groups.

Table.
Speech Intelligibility Index data for average probe microphone data.

Subject Group	Old Aid	Directional	Omnidirectional
Mild	0.776	0.773	0.760
Moderate	0.743	0.744	0.723
Severe	0.679	0.671	0.659

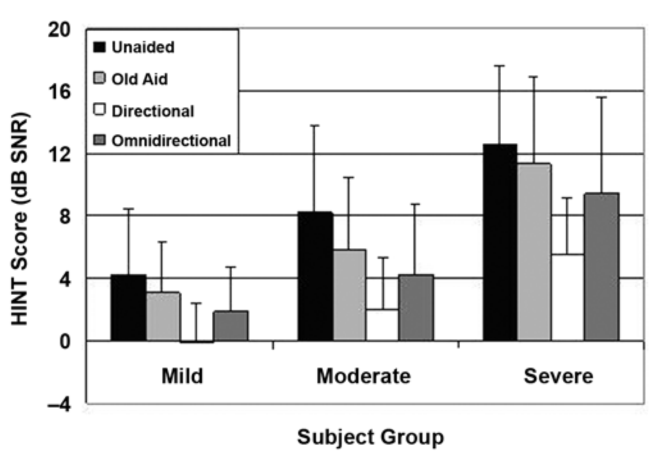

Figure 8.
Hearing in Noise Test (HINT) results. SNR = signal-to-noise ratio.

CST

CST data are shown in **Figure 9**. An ANOVA indicated significant main effects of hearing loss group ($F_{2,6} = 40.65$, $p < 0.001$) and hearing aid condition ($F_{3,6} = 64.7$, $p < 0.001$). We used the Tukey HSD analysis to further delineate the source of the significant main effects. With respect to hearing loss group, the mean CST scores differed significantly in all three groups. Similar to the HINT data, the performance on the CST was best for the mild group, followed by the moderate group, and worst for the severe group. The follow-up analysis on the main effect of hearing aid condition indicated that all means for the hearing aid conditions differed significantly from one another, with the exception of old aid condition and the experimental aid in the omnidirectional setting. Once again, the pattern of the results indicated that the best performance was achieved in the directional condition followed by the omnidirectional and old aid conditions, with the lowest scores on the CST in the unaided conditions. As was the case for the HINT data, we found no significant interaction effects.

PHAB

Figure 10 shows the overall means on the PHAB. An ANOVA yielded a significant main effect of hearing aid condition ($F_{3,6} = 35.7$, $p < 0.001$). We found no effect of hearing loss group or interaction effect. A follow-up analysis on the effect of hearing aid condition indicated that the two experimental conditions (directional and omnidirectional) did not differ significantly from one another;

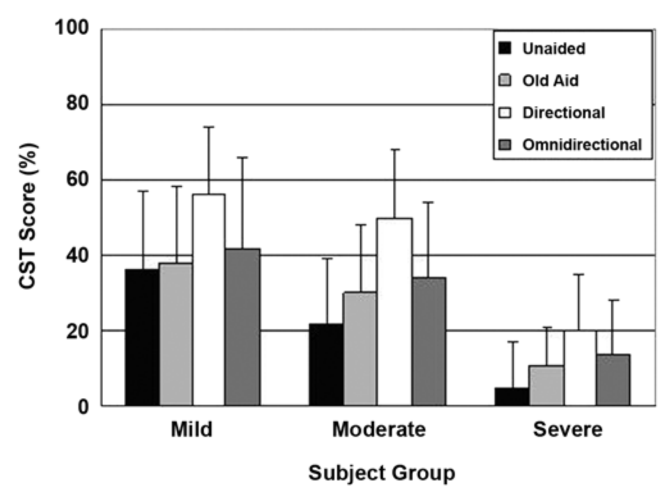

Figure 9.
Connected Speech Test (CST).

however, all other between-group comparisons were significant.

Because we found no significant main effect of hearing loss group, we combined the PHAB data for the three subject groups for subscale analysis. The data are shown in **Figure 11**. With the exception of the aversiveness subscale, the data from the other six subscales follow the same pattern as the overall mean data with the two experimental conditions (directional and omnidirectional) not significantly different from one another but superior to the old aid condition, which in turn was superior to the unaided condition. The pattern of results for the aversiveness subscale indicated similar mean scores for the unaided and the directional conditions. Both unaided and directional were rated better (less aversive) than the old aid and omnidirectional conditions, which did not differ significantly.

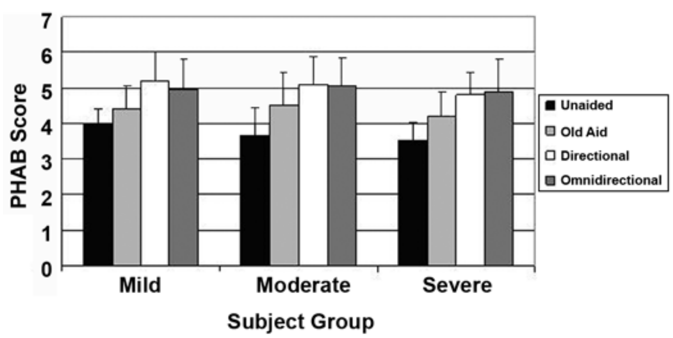

Figure 10.
Profile of Hearing Aid Benefit (PHAB) results.

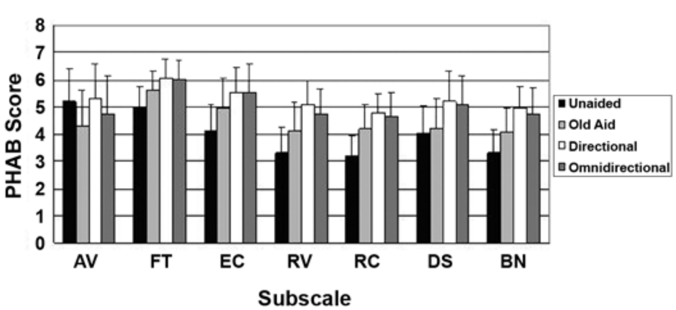

Figure 11.
Profile of Hearing Aid Benefit (PHAB) subscale results. AV = aversiveness, BN = background noise, DS = distortion of sounds, EC = ease of communication, FT = familiar talkers, RC = reduced cues, RV = reverberation.

SADL

An ANOVA on the SADL data indicated a significant main effect of hearing aid condition ($F_{2,4} = 84.6$, $p < 0.001$). The effect of hearing loss group was not significant ($F_{2,4} = 2.75$, $p > 0.05$). The SADL data were collapsed across hearing loss group and are shown in **Figure 12**. Higher SADL scores indicate better self-reported patient satisfaction.

We performed the Tukey HSD analysis to follow up on the significant main effect of hearing aid condition. For the global means and the positive effects of amplification, negative features, and personal image subscales, the pattern of the results is similar. For these measures, the mean SADL data did not differ significantly for the two experimental conditions (directional and omnidirectional), and both directional and omnidirectional conditions were rated significantly higher than the old aid condition. The exception to this pattern was for the service and cost subscale, for which the directional hearing aid condition was rated significantly higher than the omnidirectional condition, which in turn was rated higher than the old aid condition.

User-Preference Questionnaire

The user-preference data are summarized in **Figures 13, 14**, and **15**. To examine between-group differences, we calculated both chi-square analyses and Cramer's phi for both the noise and quiet conditions across the three groups. No significant differences were found between groups for either the quiet ($\chi^2 = 3.4$; $p < 0.76$) or noise ($\chi^2 = 7.4$; $p < 0.28$) conditions, and Cramer's phi was low (0.14 and 0.20 for quiet and noise, respectively), indicating that all three

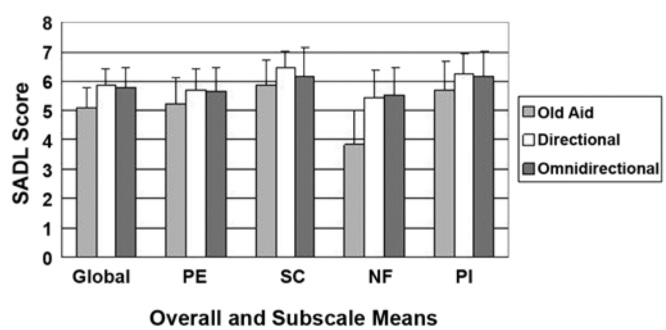

Figure 12.
Satisfaction with Amplification in Daily Life (SADL) results. NF = negative features, PE = positive effects of amplification, PI = personal image, SC = service and cost.

groups demonstrated similar preference patterns. However, we found a nonsignificant trend for more individuals in the mild group preferring the directional setting and more individuals in the other two groups preferring the omnidirectional setting. Specifically, for the mild group in the quiet condition, 53 percent of subjects preferred the directional setting, 41 percent preferred the experimental omnidirectional setting, 2 percent (1 subject) preferred the old aid, and 2 percent had no preference. In noise, 56 percent preferred directional, 28 percent preferred omnidirectional, 6 percent preferred the old aid, and 9 percent had no preference. The overall preferences followed a pattern similar to the quiet and noise ratings: 50 percent preferred the directional, 36 percent preferred the omnidirectional, 6 percent (2 subjects) preferred the old aid, and 6 percent reported no preference.

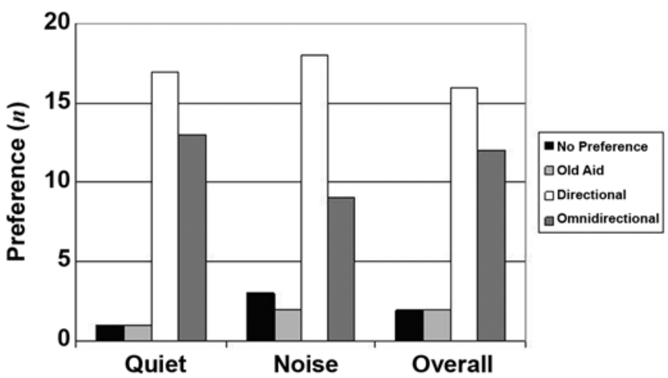

Figure 13.
Hearing aid preference, mild group.

Figures 14 and **15** show user-preference data from the moderate and severe groups. In both groups, the overall preference favored the experimental omnidirectional (53% for the moderate group and 48% for the severe group). Similarly, in the quiet condition, 50 percent of subjects in the moderate group and 52 percent of subjects in the severe group preferred the omnidirectional program. The ratings in noise also favored the omnidirectional setting (56% for the moderate group, 52% for the severe group). The number of subjects with no preference or a preference for the previous aid was relatively low.

DISCUSSION

Objective Measures

The results from the HINT and CST administration provide several noteworthy details. Perhaps most important is that hearing aids improve understanding. While a number of studies look at a variety of hearing-aid-processing schemes and features, verifying that hearing aids are indeed helpful both in terms of research and clinical practice is always valuable. These data indicate that even in a difficult listening environment with noise surrounding the listener and a moderate degree of reverberation, hearing aid users can expect significantly better understanding with their aids than without. All the hearing aid conditions resulted in significantly better performance than the unaided condition. The value of this finding should not be underestimated.

Another significant conclusion that can be drawn from the speech-in-noise data is that directional microphones improve speech understanding in noise. The two measures

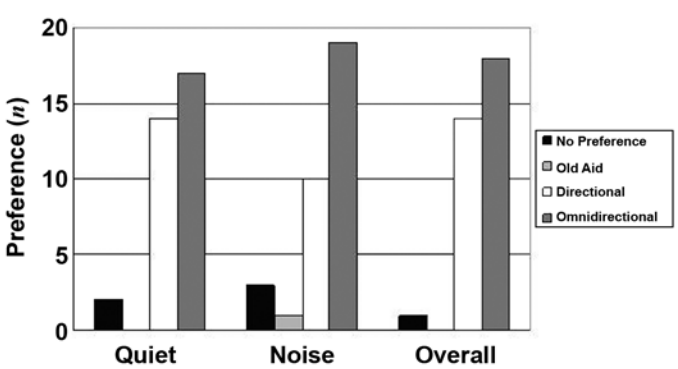

Figure 14.
Hearing aid preference, moderate group.

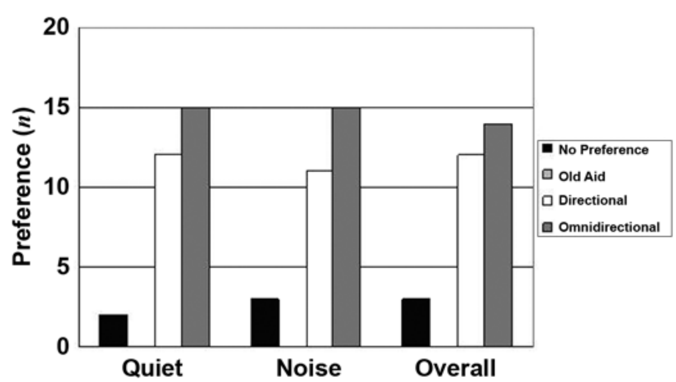

Figure 15.
Hearing aid preference, severe group.

of speech understanding in noise were chosen to represent real-world SNRs in difficult listening environments. The HINT assesses the SRT in terms of SNR for 50 percent correct identification of sentence materials, while the CST data are scored as percent correct for a fixed SNR. In both cases, for all hearing loss groups, the experimental hearing aid set to the directional mode showed significantly better performance than unaided, the subject's old hearing aid, or an experimental aid set in an omnidirectional setting.

For both speech-in-noise test materials, the directional condition resulted in the best performance, followed by the omnidirectional condition. This finding was expected because of the reduction of gain for sounds originating from rear azimuths. The experimental omnidirectional setting resulted in better scores on the HINT than did the old aid setting. While not reaching statistical significance when evaluated with the CST, **Figure 9,** upon visual inspection, suggests a similar trend of slightly better performance on the omnidirectional than the old aid condition. We made concerted efforts in the design of this study to control for variables other than the directionality of the hearing aids. The old aids and experimental aids were the same sizes and styles, used the same processing scheme, and were fit using the same protocol. Thus, we expected that on both the HINT and CST the performance in noise would be similar for the two omnidirectional conditions (old aid and experimental omnidirectional). Although the average performance differences were small, the trends in both the HINT and CST data did not support this expectation.

An interesting finding with respect to the degree of hearing loss was that the same pattern of results remains constant across all three groups. Although the absolute scores on the HINT and CST decrease with increasing hearing loss, the benefit from omnidirectional to directional remains. The finding of consistent benefit across hearing aid groups is clinically relevant. These data indicate that in terms of speech intelligibility in noise, individuals with all degrees of hearing loss will potentially significantly benefit from directional-microphone hearing aids. Despite significant directional benefit being measured across all hearing loss groups, the magnitude of directional benefit for listeners in the severe hearing loss group was considerably smaller than in the two other groups when measured by the CST (approximately 7% compared with approximately 18%–22%). In contrast, more similar directional benefit was evident across hearing loss groups as measured by the HINT. The finding of reduced directional benefit in listeners with severe hearing loss at a fixed SNR compared with listeners with mild and moderate hearing loss are consistent with those of Ricketts and Hornsby [29]. This reduction in directional benefit with increasing hearing loss at fixed SNRs is expected because of hearing loss desensitization [49]. That is, the same improvement in SNR was available to all three subject groups, leading to similar directional benefit as measured by the HINT. However, for materials presented at a fixed SNR, that same effective increase in SNR resulting from directional processing expectedly led to smaller improvements in speech-intelligibility scores with increasing hearing loss as measured by the CST.

Subjective Measures

Although the objective data clearly show an advantage for the directional-microphone condition, the subjective data do not support the directional advantage as strongly. The PHAB data showed significantly better performance in the three aided conditions than in the unaided condition. Both of the experimental conditions were consistently rated higher than the old aid condition. For the PHAB, the only condition in which directional was rated significantly better than omnidirectional was the aversiveness subscale, on which a subject rates the degree to which sounds (especially loud sounds) are bothersome. Interestingly, the mean for the directional condition did not differ significantly from the unaided condition, indicating that in directional mode subjects did not perceive sounds as any more aversive than if they had no hearing aid at all. The omnidirectional condition and old aid condition both scored significantly poorer for this subscale.

We should note that subjects were given instructions under both experimental conditions to switch to the second program for situations in which for safety purposes they needed to hear sounds all around (e.g., crossing the street in traffic). Subjects were asked to record in their usage log the proportion of the time (if any) they used the second program. No subject reported using the second program more than a few minutes per week. Additionally, the hearing aids always defaulted to the experimental (first) program any time the devices were turned off and back on. Thus, we assumed that the data reported for the directional condition were not contaminated by the subject accidentally using the omnidirectional (second) program.

The results from the SADL show a pattern similar to that of PHAB with the omnidirectional and directional experimental conditions consistently rated as more satisfactory than the old aid condition. The only exception to this pattern of results is for the service and costs subscale of the SADL, on which subjects rated that they were more satisfied with the directional setting than with either the omnidirectional or old aid conditions.

Neither of the subjective measurements showed any significant effect of degree of hearing loss. This finding indicates that regardless of the degree of pure-tone loss, these subjects reported similar hearing aid performance and satisfaction. We would expect that aided performance would be better in a mild hearing loss group than in a severe group. For satisfaction data, we would not necessarily expect a difference based on degree of hearing loss alone.

Given the relative equality of the ratings for the omnidirectional and directional conditions, placebo and experimental effects cannot be ruled out. Both subjects and experimenter were blinded to the hearing aid settings for administration of the objective and subjective scales. Subjects were instructed that this study was evaluating different ways that hearing aids work in background noise. We made every attempt to keep the size and appearance of the experimental aids consistent with the wearers' old aids. Nonetheless, the experimental hearing aids were new and did have a remote control, something that their previous aids did not. Additionally, that these hearing aids were provided to a veteran population at no cost may have influenced the results. The presence of a large and significant advantage for the experimental omnidirectional condition compared with the old hearing aid condition, even though these instruments were matched as closely as possible, and only a small improvement in speech recognition, supports the presence of a halo effect for the experimental hearing aids. This halo effect also was apparent in the hearing aid preference data. We speculate that the magnitude of this halo effect may have been so dominant that little room was left for additional subjective improvement related to the directional mode. Despite this argument, research has shown that the broad nature of the questions asked in the general subscales of measures like the PHAB can obscure self-reported directional benefit [40]. For example, the background noise subscale includes noisy environments in which both omnidirectional benefits and directional benefits are expected. The current data lend further support for the hypothesis that self-perceived directional benefit is either limited in magnitude, not readily measured using general outcome measures, or both.

User-Preference Questionnaires

Although the three hearing loss groups did not differ significantly in their pattern of preference, the majority of subjects in the mild hearing loss group showed a preference for the directional mode in all conditions (quiet, noise, and overall). The majority of listeners with moderate and severe hearing loss preferred the omnidirectional setting. The source of these preferences is not readily apparent, but several possibilities exist. Possibly, the preferences of the subjects were based on gain differences. Although we made every attempt to match frequency responses between the directional and omnidirectional conditions and the SII scores were similar, we found patterns of differences in the target matches between groups. On average, less low-frequency gain was achieved in the directional mode for the more severe losses because of the inherent reduction of low-frequency energy with directional systems. Thus, the subjects in the moderate and severe groups who were long-time hearing aid users could have preferred the omnidirectional setting because of the increased low-frequency gain available in this condition, despite the relative equality of overall audibility. Additionally, subjects could have preferred the omnidirectional microphone condition because of the greater access to environmental cues that was likely afforded in this program.

The subjects in the mild group had a greater preference for the directional-microphone setting. While ideally this could be attributed to the advantages of the directional microphone in terms of speech understanding in noise, these subjects did not differentiate their preferences in quiet from their preference in noise, which may indicate that other factors played a role in these ratings. Because subjects in the mild group exhibited, on average, near normal hearing in the low frequencies, less gain for low-frequency stimuli may possibly have afforded them more listening comfort and/or less microphone noise. The source(s) of the listening preferences were not directly assessed in this investigation. However, we speculate that, given the potential limitations of full-time use of the directional mode, preferences in individual listeners may have resulted from each unique subject's listening environments, low-frequency gain differences, and the frequency of directional benefits and decrements.

Finally, subjects were told during each phase of the trial that they would likely perform better in noise if they positioned themselves with the signal of interest in front of them and the competing noise behind them. However, we received no verification from subjects that they performed in this manner. Thus, the possibility exists that the SNR advantages shown on the HINT and CST were not realized in the real world because of the failure of subjects to position themselves for optimal directional benefit. This may be an area for increased focus during hearing aid orientation and follow-up counseling, as significant advantages were shown in the speech testing but not in the subject-reported data.

CONCLUSIONS

Ninety-four subjects completed the double-blinded trial with omnidirectional and directional settings programmed into the experimental hearing aids. Subjects in the three hearing loss groups wore the aids in each of the two experimental settings for 1 month before returning for speech-in-noise testing and laboratory-administered self-assessment questionnaires. The objective measures of speech understanding in noise strongly favored the directional setting for both tests across all hearing loss groups. The lack of significant interaction effects indicated that the degree of benefit from the directional-microphone hearing aids was consistent across the mild, moderate, and severe hearing loss groups. These data support the use of directional-microphone hearing aids for all degrees of hearing loss included in this study. Specifically, the severe-to-profound group showed significant improvements in speech intelligibility in noise with directional microphones.

The results of the subjective measurements demonstrated a considerable halo effect related to the experimental hearing aids. Subjective data did not strongly support an exceptional real-world advantage to directional setting within the experimental hearing aid conditions. These findings are consistent with previous research, suggesting that general subjective measures may lack the sensitivity to capture the differences in speech understanding in noise between the two experimental hearing aid settings. Despite this argument, frequency-response differences between the programs, experimental and placebo effects, and the potential failure of subjects to properly use/position themselves with the hearing aids in background noise may have also contributed to this finding.

Taken together, the objective and subjective data indicate the potential for significant improvements in speech understanding in noise with directional-microphone hearing aids for clinical patients with varying degrees of hearing loss. The lack of significant differences in subjective data, however, indicates that either our measures do not directly address situations where directional microphones are advantageous or our investigators failed to effectively instruct patients in the proper use of directional hearing aids. Clinically, we recommend the use of directional hearing aids when possible for patients with varying degrees of hearing loss and strongly recommend counseling patients on the best practices and positioning when using these devices.

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Author Contributions:
Study concept and design: D. Gnewikow, T. Ricketts, G. W. Bratt.
Acquisition of data: L. C. Mutchler, D. Gnewikow.
Analysis and interpretation of data: D. Gnewikow, T. Ricketts.
Drafting of manuscript: D. Gnewikow, T. Ricketts.
Critical revision of manuscript for important intellectual content: D. Gnewikow.
Statistical analysis: D. Gnewikow, T. Ricketts.
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