Comparison of Performance across Three Directional Hearing Aids

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Abstract

This study compared the speech recognition performance of 12 hearing-impaired listeners fit with three commercially available behind-the-ear hearing aids in both directional and omni-directional modes. One digitally programmable analog and two "true digital" hearing aids were selected as test instruments. Testing was completed in both "living room" and anechoic room environments. Speech recognition was examined using modified forms of the Hearing in Noise Test and the Nonsense Syllable Test. The single competing stimuli of these tests were replaced with five uncorrelated competing sources. Results revealed a significant speech recognition in noise advantage for all directional hearing aids in comparison to their omnidirectional counterparts. Maximum performance of the directional hearing aids did not significantly vary across circuit type, suggesting that processing differences did not affect maximum directional hearing aid performance. In addition, the results suggest that performance in one reverberant environment cannot be used to accurately predict performance in an environment with differing reverberation.

Key Words: Digital hearing aids, digitally programmable hearing aids, directional microphones, hearing aid performance

Abbreviations: A = Phonak Piconet P2 AZ™ omnidirectional; AD = Phonak Piconet P2 AZ™ directional; BTE = behind the ear; HINT = Hearing in Noise Test; KEMAR = Knowles Electronics Manikin for Acoustic Research; NST = Nonsense Syllable Test; P = Siemens Prisma omnidirectional; PD = Siemens Prisma™ directional; PV = Siemens Prisma omnidirectional with maximum VAD; S = Widex Senso™ omnidirectional; SD = Widex Senso directional; SNR = signal-to-noise ratio; TD = threshold of discomfort; VAD = voice activity detector; WDRC = wide dynamic range compression

One of the most common complaints of hearing aid wearers continues to be speech understanding in the presence of background noise. The most commonly used strategies to improve signal-to-noise ratio (SNR) in hearing aids are those that reduce the output of the "noise" in frequency ranges other than those important for speech intelligibility (for review, see Bentler et al, 1993). This presents an obvious problem when the noise either spectrally resembles, or actually is, speech. Directional microphones continue to be one of the few methods for increasing SNR within the same frequency band in hearing aids, and one of the only approaches to enhancing speech intelligibility in noise that has shown significant benefit over a wide range of hearing-impaired listeners. Recently, several studies have reported significant improvement in speech intelligibility in noise with the use of directional microphones (Valente et al, 1995; Agnew and Block, 1997; Voss, 1997; Killion et al, 1998). This renewed interest reflects improvements in design and implementation of directional microphones in hearing aids, including their application to in-the-ear devices.

A number of issues are important when evaluating directional microphone hearing aids. Variance in test parameters such as noise type, number of noise sources, test material, and acoustic properties of the test environments

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often make it difficult to compare results across investigations. Assessment of the relative benefit provided across various hearing aids using directional microphones remains an important but unanswered question. In addition, the choice of test parameters in many previous investigations makes it difficult to predict benefit achieved in the real world. Of special concern are the competing noise parameters and the reverberation times of the environments selected. Testing with multiple, uncorrelated noise sources in a test environment with moderate (approximately 0.5-second) reverberation levels may provide a measure that is a more realistic predictor of real-world performance. In contrast, however, most recent investigations of directional hearing aids have used a single noise source (e.g., Valente et al, 1995; Lurquin and Rafhay, 1996) or multiple, but correlated, noise sources (e.g., Voss, 1997) presented in relatively nonreverberant environments (usually sound-treated test booths).

Comparison across hearing aids that implement directional microphone technology is important for a number of reasons. In addition to differences specifically related to the directional microphones, other variables, such as the signal-processing algorithm used, could influence the measured directional benefit. For example, the availability of digital signal processing in recent hearing aids has enabled manufacturers to use novel noise identification and rejection algorithms in addition to directional microphone technology. In general, these algorithms attempt to categorize signals according to their temporal patterns. Signals identified as "steady state" are assumed to be noise and reduced in level, while fluctuating signals are assumed to be speech and passed through. The use of such algorithms adds to the complexity of estimating the benefit obtained from these hearing aids.

The purpose of this investigation was to evaluate the speech recognition performance provided across three commercially available directional behind-the-ear (BTE) hearing aids. The hearing aids selected for this study were the Phonak Piconet P2 AZ™, the Siemens Prisma™, and the Widex Senso™. The Siemens and the Widex products are true digital instruments while the Phonak instrument is a digitally programmable analog hearing aid. The Phonak and the Siemens instruments can be used in both single-microphone omnidirectional mode and dual-microphone directional mode through a remote control or a switch on the hearing aid. Widex, on the other hand, has two separate

products, the C8 being the omnidirectional aid and the C9 being a single-microphone directional hearing aid. The Widex and Siemens products also use digital noise identification and rejection algorithms. In the Widex product, this algorithm is always active, whereas in the Siemens instrument, it (described as the voice activity detector [VAD]) can be activated at two different levels ("medium" and "maximum") or left deactivated. The specific parameters of these algorithms are unknown due to proprietary constraints.

PROCEDURES

Subjects and Methods

Subjects included 12 adult listeners with sloping, symmetric, mild to moderately/severe, sensorineural hearing impairment (Fig. 1). Pure-tone thresholds and acoustic immittance measures were obtained prior to the test session. All subjects exhibited no significant air–bone gap at any frequency (>10 dB) and normal type A tympanograms (compensated static admittance between 0.35 and 1.65 mmho measured from the positive tail with tympanometric peak pressure between −75 and +75 daPa). Loudness growth patterns at octave frequencies from 500 Hz through 4000 Hz were obtained using the Contour Test (Cox, 1997) and thresholds of discomfort (TD) were assigned based on category 7 ("too loud") ratings. Threshold and TD data were used with the NOAH™ hearing aid fitting software for calculation of all gain and compression parameters using each of the manufacturer's (Phonak, Siemens, and Widex) hearing aid fitting modules.
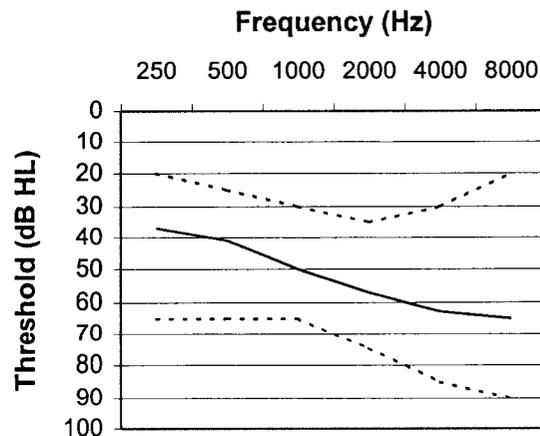

Figure 1 Range and average of the hearing thresholds measured for all 12 experimental subjects.

Speech recognition measures were obtained on subjects in unaided and seven hearing aid conditions. The hearing aid conditions included the following binaurally fit BTE hearing aids: (1) Phonak Piconet P2 AZ™ directional (AD); (2) Phonak Piconet P2 AZ™ omnidirectional (A); (3) Siemens Prisma™ directional (PD); (4) Siemens Prisma omnidirectional (P); (5) Siemens Prisma omnidirectional with maximum VAD (PV); (6) Widex Senso™ omnidirectional (S); and (7) Widex Senso directional (SD). For each subject, all hearing aids were coupled to the ear using a custom Lucite, full-shell earmold with a 3-mm Libby horn and 1-mm pressure relief venting. Gain and output were assigned for all Siemens conditions using the "first-fit" algorithm (a modified Desired Sensation Level (DSL) input/output scheme with no additional adjustments). All Widex fittings were accomplished through the use of the Sensogram™ after feedback testing (no additional adjustments). Wide dynamic range compression (WDRC) was selected for all Phonak fittings resulting in the use of low-threshold compression across all seven hearing aid conditions. All Phonak conditions were fit using the "Loud-Norm" algorithm as suggested by the manufacturer when implementing WDRC (no additional adjustments). The choice of the first listening condition tested was counterbalanced across all eight conditions. The remaining listening conditions were fully randomized within and across subjects.

Following each test session, gain measurements were obtained across all hearing aid conditions. While measurement of real-ear insertion gain is possible for the Phonak and non-VAD Siemens fittings, its measurement on the Widex and Prisma +VAD hearing aids is not possible using traditional signals. This is due to the fact that these algorithms reduce gain in the presence of steady-state signals. In order to compare the assigned gain across all listening conditions, a six-component composite noise (500, 1000, 2000, 3000, 4000, 5000 Hz), which was 75 percent amplitude modulated at 3 Hz, was generated as a test signal. This test signal was spectrally shaped to match the long-term average speech spectrum assumed for the Speech Intelligibility Index (ANSI, 1997). Aided and unaided output in response to this test signal presented at 65 dB SPL was measured in a Zwislocki coupler mounted in a Knowles Electronics Manikin for Acoustic Research (KEMAR) to provide a measure of gain. All measurements were obtained at 0° azimuth in an anechoic chamber with the KEMAR placed 1 meter from the source speaker. The hearing aids were coupled to the KEMAR using an earmold identical to that used for the test subjects. These measures were made for all seven hearing aid conditions given the calculated prescriptions for each subject.

Speech recognition testing was performed for two different reverberation conditions, an anechoic room and a "typical living room" listening environment (carpeted floor, sound tiled ceiling, curtains on all windows, and upholstered furniture). Reverberation time (time required for 60-dB decay after signal offset) of the "living room" environment was measured with frequency modulated tones (center frequencies of 500, 1000, 2000, and 4000 Hz) at the position of the listener's head. Average reverberation time was 642 msec. A modified Hearing in Noise Test (HINT) and a modified Nonsense Syllable Test (NST) served as test material in the reverberant room, while only testing using the HINT was performed in the anechoic room. All reverberant room testing was done during 2-hour test sessions on two separate days. Testing in the anechoic room was completed in one 2-hour session on a third test day.

The modified speech recognition tests were presented from compact disk via three Onkyo CD players and three Denon stereo amplifiers. Subjects were seated in the center of each of the test environments and the test stimuli were presented at 0° azimuth from a McIntosh TH-1™ speaker. This speaker provides a directional output similar to those obtained from a talker at 1 meter. Competing noise was presented from five Optimus Lineaum™ speakers placed at 90°, 135°, 180°, 225°, and 270° azimuth. The dipole design of these speakers provides a more diffuse sound field than traditional forward-firing speakers. Average polar patterns measured in response to a speech-shaped noise stimuli are shown in Figure 2.

Speech Recognition Test Modification

The HINT (Nilsson et al, 1994) was developed to measure speech intelligibility with sentence materials over a range of listening conditions from quiet to noise without spatial separation. The HINT requires listeners to repeat sentences spoken by a male talker in the presence of speech-shaped noise presented at a fixed level (65 dBA SPL). Scoring is accomplished for either one or two 10-sentence blocks. It is assumed that speech-shaped noise is used in lieu of noises more similar to "real-world" environments (e.g., multitalker babble, cafete-
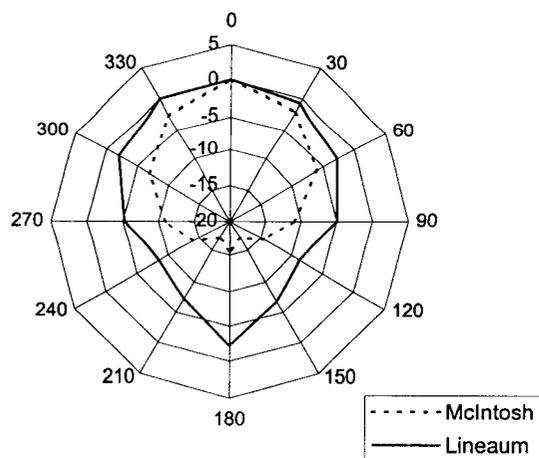
Figure 2 Average polar directivity patterns measured for the two speaker types used in this study. The output of these speakers were measured at 30° increments in an anechoic chamber using a 70 dB SPL speech-weighted noise.

ria noise) due to the stability of signal level. This stability has the effect of increasing the reliability of individual signal-to-noise ratio (SNR) measures when compared to a signal that shows greater level variance across time. The standard competing signal was replaced with cafeteria noise for this study. Cafeteria noise was selected for this modification due to its similarity to "real-world" environments. This noise was digitally recorded in a noisy (80 dBA) university cafeteria using a Sony digital audiotape recorder. To address the fluctuations in level, the rms level of the cafeteria noise was normalized using 0.5-msec attack and release times. Five 1-minute, 20-second, nonoverlapping sections (ensuring no correlation) of this processed cafeteria noise were selected for use as the five competing noise sources across all modified HINT lists. The noise sources were then filtered to provide a long-term average spectral shape identical to that of the test stimuli. All sound modification (including arrangement, normalization, and filtering) and analysis was accomplished offline through the use of a Pentium II computer and Sound Forge™ sound modification software with the Spectral Analysis plug-in. Measurement of the combined noise sources revealed a level fluctuation of no more than ± 0.53 dB across all items. For the purposes of this experiment, two 10-sentence blocks were used for each test condition. Presentation level of the sentences was adaptively adjusted depending on the subjects' response (an incorrect response raises the level, and a correct response lowers the noise level for

the next presentation) according to HINT guidelines. The signal level of the sentence stimuli was varied in 4-dB (first 5 trials) and 2-dB (final 15 trials) steps.

The NST (Resnick et al, 1975) was presented as a second test of speech intelligibility in noise. The NST was chosen for the present study because, unlike monosyllabic word tests that vary in vowel context, vowel environment is held constant within each subtest, allowing for consonant error analysis (Dubno, 1978). Due to the use of nonsense syllables, this test may be more free of context and learning effects in comparison to traditional tests of speech discrimination (Resnick et al, 1975). The NST was first modified by digitally recording the corresponding multitalker babble and dividing this noise signal into five equal blocks. Arranging these five noise blocks in a pseudorandom fashion generated five new noise signals. The pseudorandom arrangement ensured that the resultant five channels of noise were fully uncorrelated. The presentation level of individual NST items (including carrier phrase and corresponding noise signals) was randomly varied over a 25-dB range (58–82 dB SPL) in 6-dB steps in an attempt to simulate level differences noted across speakers during routine conversation (ANSI, 1997). This was accomplished by digitizing each item (with carrier phrase) and randomly assigning an intensity level prior to playback. All digital modification and analysis of the NST was accomplished using the same equipment and software used for the HINT modifications. It has been proposed that this test may better reflect speech recognition performance over the full range of average talker levels (Ricketts and Bentler, 1997). All lists of the modified NST were presented at a +8 SNR across all conditions.

After completing the modifications described above, the six tracks (one primary and five competing noise stimuli) of both the modified HINT and NST were recorded to three compact disks for test presentation. Test presentation order within and across both the HINT and NST were fully randomized.

RESULTS

Reverberant Room Results

A comparison of HINT results across hearing aid conditions is shown in Figure 3. One-way analysis of variance across all omnidirectional and directional hearing aid conditions (all omnidirectional vs all directional) revealed a signif-
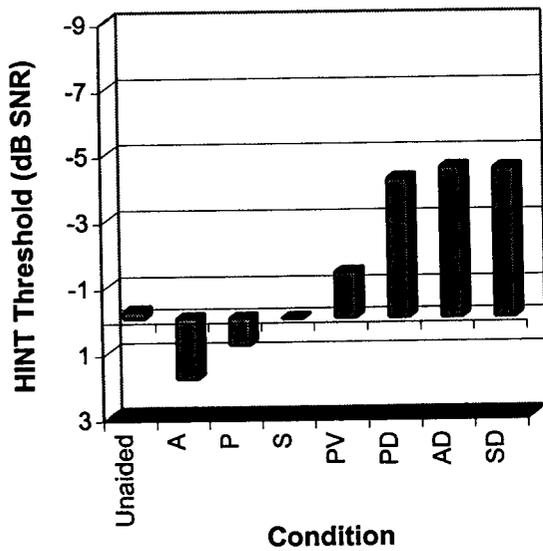
Figure 3 Average HINT SNR thresholds for 12 subjects across all listening conditions measured in the "living room" environment.
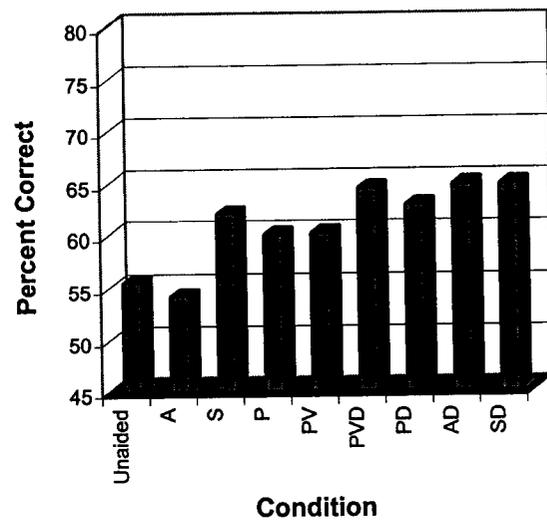

Figure 4 Average NST scores for 12 subjects across all listening conditions measured in the "living room" environment.

icant difference (p < .001; f = 27.91; df = 1). Tukey honest and significant difference (HSD) post hoc testing revealed that subjects performed significantly better when fit with directional amplification in comparison to omnidirectional (p < .01). One-way analysis of variance across individual listening conditions revealed a significant difference across conditions (p < .01; f = 4.44; df = 7). Tukey HSD post hoc testing revealed that subjects performed significantly better (p < .05) when fit with the Prisma directional (PD), AZ directional (AD), and Senso directional (SD) conditions than with any of their omnidirectional counterparts (Table 1). No other significant differences were noted.

A comparison of NST results across hearing aid conditions is shown in Figure 4. One-way analysis of variance across all omnidirectional and directional hearing aid conditions (all omnidirectional vs all directional) revealed a significant difference (p = .027; f = 3.57; df = 1). Tukey HSD post hoc testing revealed that subjects performed significantly better when fit with direc-

tional amplification (p = .045). One-way analysis of variance across individual listening conditions revealed a significant difference across conditions (p = .049; f = 2.79; df = 7). Tukey HSD post hoc testing revealed no significant differences. No other significant differences were noted.

Individual data followed group trends as all subjects performed the best with one of the directional schemes and poorest for either one of the omnidirectional schemes or when unaided across both speech recognition tests. Prior to this investigation, test–retest data were obtained for all 12 20-item (two-block) lists of the modified HINT used in this investigation. The data were collected for 20 unaided listeners that exhibited sensorineural hearing loss consistent with the criteria set forth in this experiment. Testing was performed on two different days separated by at least 1 week. Standard error of measure (SEM) was calculated from the standard deviation of differences between repeated measurements within subjects. The corre-

Table 1 Tukey HSD Significance Values for the Modified HINT across Selected Listening Conditions as Measured in the "Living Room" Environment

	Prisma	AZ	Senso	Unaided
Prisma directional	p = .01	p < .01	p = .047	p = .092
AZ directional	p = < .01	p < .01	p = .031	p = .067
Senso directional	p < .01	p < .01	p = .033	p = .055

sponding 95 percent confidence interval was 1.86 dB, suggesting that this difference is representative of a significant difference within individuals. This is in fair agreement with the data of Nilsson et al (1994), which indicated 20-item confidence intervals (95%) for the unmodified HINT ranging from 1.20 to 1.51 dB, depending on noise azimuth. SEM data combined with individual data from this experiment did not reveal a "best-performing" directional hearing aid. Specifically, only 4 of the 12 subjects exhibited a maximum HINT score of at least 1.9 dB SNR better than any other condition. Of these, two subjects performed best with the AD and two with the PD fitting condition. Five of the remaining eight subjects revealed less than a 1-dB difference in performance (from the maximum score) for at least two of the three directional conditions.

Anechoic Chamber Results

A comparison of HINT results across hearing aid conditions as measured in the anechoic chamber is shown in Figure 5. One-way analysis of variance across all omnidirectional and directional hearing aid conditions (all omnidirectional vs all directional) revealed a significant difference (p < .001; f = 34.86; df = 1). Tukey HSD post hoc testing revealed that subjects performed significantly better when fit with directional amplification in comparison to omnidirectional (p < .01). One-way analysis of variance across individual listening conditions revealed a significant difference across conditions (p < .01;
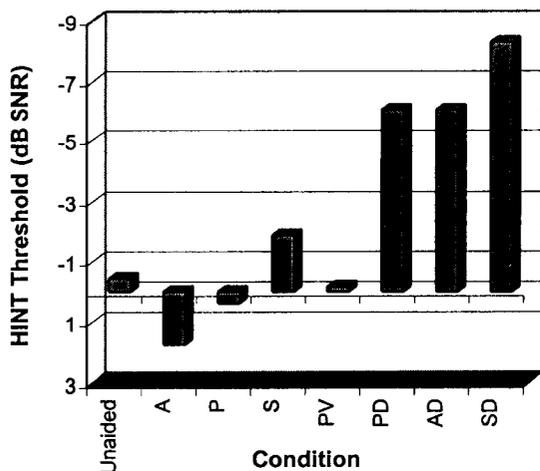
f = 6.53; df = 7). Tukey HSD post hoc testing revealed that subjects performed significantly better when fit with any (AD, PD, SD) of the directional conditions in comparison to the omnidirectional conditions or when unaided (Table 2). No other significant differences were noted. Individual data followed group trends as all subjects performed the best with one of the directional schemes and poorest for either one of the omnidirectional schemes or unaided. A "best-performing" directional hearing aid was again not clearly evident; however, 6 of the 12 subjects exhibited a maximum HINT score of at least 1.9 dB SNR better than any other condition. All six of these subjects performed the best with the SD fitting condition. All six of the remaining subjects revealed less than a 1-dB difference in performance (from the maximum score) for at least two of the three directional conditions.

KEMAR-mounted Zwislocki coupler gain across all omnidirectional and directional fitting conditions is shown in Figures 6 and 7, respectively. When examining the omnidirectional fittings, it is evident that the Phonak provided at least 11 dB more gain at 500 and 1000 Hz than all other fittings. Further, it is evident that, on average, both the Phonak and Siemens directional fittings provided substantially less low-frequency gain than their omnidirectional counterparts, while the directional and omnidirectional Widex fittings provided nearly identical gain throughout the entire frequency range.

DISCUSSION

I n terms of speech recognition measures, the advantage of hearing aids with directional microphones is readily apparent, given these data. Specifically, significant differences were noted for directional microphones over their omnidirectional counterparts in two different environments (moderately reverberant and anechoic) and for two different noise backgrounds (multitalker babble and cafeteria noise). As might be expected, the directional advantage was somewhat greater (approximately 2–3 dB) in the anechoic room than in the more reverberant room. In addition, the performance pattern varied across the two environments. The slightly better performance noted for some subjects fit with the SD condition in the anechoic room (in comparison to the other directional conditions) was not seen in the reverberant room. In addition, the slight performance enhancement noted for the PV condition (in

Figure 5 Average HINT SNR thresholds for 12 subjects across all listening conditions measured in the anechoic room.

Table 2 Tukey HSD Significance Values for the Modified HINT across Selected Listening Conditions as Measured in the Anechoic Chamber

	Prisma	Prisma + VAD	AZ	Senso	Unaided
Prisma directional	p < .01	p < .01	p < .01	p = .045	p < .01
AZ directional	p < .01	p < .01	p < .01	p = .046	p < .01
Senso directional	p < .01	p < .01	p < .01	p < .01	p < .01

comparison to the other omnidirectional conditions) as measured by the HINT in the reverberant environment was not seen in the anechoic room. These data suggest that reverberation may not only affect the absolute performance but also the relative performance across directional hearing aids. This underscores the importance of measurement of performance under conditions that reflect real-world listening environments. While these differences were not significant and the number of subjects was small, they at least suggest caution when predicting both absolute and relative performance in one reverberant environment from measurements in another.

The advantages of the directional hearing aids compared to their omnidirectional counterparts (measured in the reverberant environment) were 2 to 3 dB poorer than recently reported for two-microphone directional hearing instruments using a single noise source placed at 180° azimuth (Valente et al, 1995; Agnew and Block, 1997). It is assumed that these differences reflect the combination of differences in reverberation time of the listening environment (previous studies were done in a sound booth) and noise presentation azimuth. While the effect of reverberation time has been examined previously (Hawkins and Yacullo, 1984), it appears that a controlled study examining the effects of noise azimuth is necessary in order to better predict "real-world" performance.

Within the reverberant environment, the results reveal some differences in the directional versus omnidirectional advantage across the speech tests. Most notable is the relative lack of significant differences across hearing aid conditions measured by the NST. On the surface,
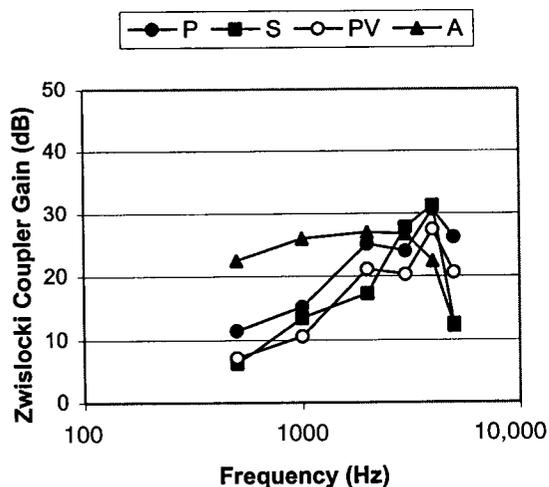

Figure 6 A comparison of in-situ Zwislocki coupler gain across all omnidirectional hearing aid conditions. Measurements were made at 0° azimuth in an anechoic chamber using a six-component (500, 1000, 2000, 3000, 4000, 5000 Hz), 75 percent amplitude modulated (3 Hz) composite noise presented at 65 dB SPL. The test signal was spectrally shaped to match the long-term average speech spectrum assumed for the Speech Intelligibility Index (ANSI, 1997).
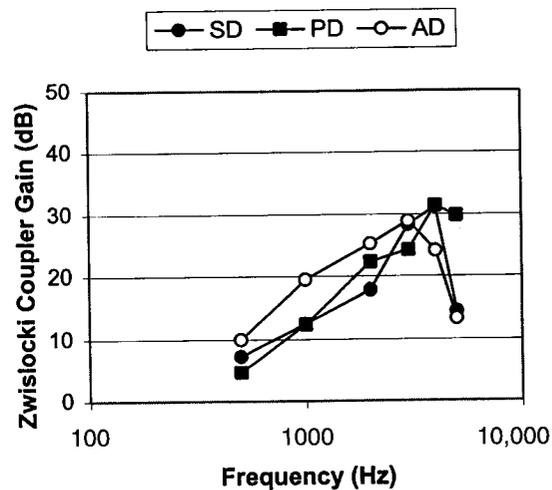

Figure 7 A comparison of in-situ Zwislocki coupler gain across all directional hearing aid conditions. Measurements were made at 0° azimuth in an anechoic chamber using a six-component (500, 1000, 2000, 3000, 4000, 5000 Hz), 75 percent amplitude modulated (3 Hz) composite noise presented at 65 dB SPL. The test signal was spectrally shaped to match the long-term average speech spectrum assumed for the Speech Intelligibility Index (ANSI, 1997).

these results are surprising, given the significant directional benefit reported in previous studies using a fixed SNR (Mueller and Johnson, 1979; Voss, 1997). It is hypothesized that the noise level used in this investigation was too favorable to demonstrate the full magnitude of the directional advantage evident in the HINT results. Specifically, the +8 SNR used in this experiment was approximately 15 to 30 dB higher than that used in previous investigations. Mueller and Grimes (1977) have pointed out that it is difficult to determine the proper SNR to use for assessing directional advantage. While the most defensible position is to select a ratio that corresponds to what a listener will most often encounter, real-world SNRs vary greatly, and the typical SNRs experienced by the patient are not known. It is evident that if a high (favorable) SNR is selected, the benefit of even the best directional microphone will be minimized. While the greatest benefit will be realized in the most difficult SNR conditions, if this SNR condition is worse than encountered in the real world by the patient, the amount of true directional hearing aid benefit will be overestimated.

While the data indicated that the directional hearing aids performed almost identically in terms of maximum performance in the reverberant environment, there were small (although not significant) differences across omnidirectional performance (see Fig. 3). It might be concluded that the variable processing (e.g., digital vs analog processing and the speech detection algorithm used in the Senso) did not appear to impact maximum directional performance (either positively or negatively). An alternate explanation might be that differences in directivity provided by the directional microphones (across hearing aid types) were counteracted by differences in processing, resulting in equivalent performance. It does appear that processing differences may have impacted omnidirectional performance. Subjects performed slightly worse when fit with the Phonak omnidirectional condition (A) as compared to the other omnidirectional hearing aid conditions. While these differences were not significant, the fact that this condition resulted in HINT scores at least 2 dB poorer that any other test condition for 8 of 12 subjects suggests that this difference might approach significance with a greater number of subjects. That is, the sample population may have simply been too small to observe a significant difference across hearing aid types. Consequently, it was deemed of interest to examine reasons for this variance further.

There are at least three possible explanations for the slightly poorer performance for subjects when fit with the A condition in comparison to the other omnidirectional conditions. First, the difference could be due to the fact that this hearing aid is the only one that does not use digital processing. This reason seems highly unlikely, given the similar performance across directional fittings across all of the hearing aid conditions. A second possibility is that the directivity provided by the A condition is inferior to the other omnidirectional conditions. Some omnidirectional hearing aids have been shown to have the greatest sensitivity to sounds behind the listener (Beck, 1983). However, this does not appear to be supported by the polar patterns across these conditions (Fig. 8).

Finally, it is possible that the differences across omnidirectional conditions result from differences in prescribed gain. Specifically, the amount of low-frequency gain provided by the A condition is well above that provided across the other conditions. A number of authors have shown that excessive low-frequency gain may lead to a decrease in speech intelligibility in noisy conditions (e.g., Skinner, 1980; van Buuren et al, 1995). The possible negative impact of this frequency response would not be expected to affect the AD condition as the implementation
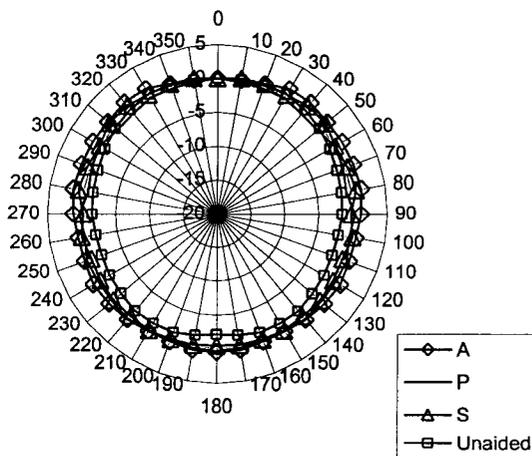

Figure 8 A comparison of the average binaural polar directivity patterns (500-, 1000-, 2000-, and 4000-Hz frequency modulated tones) measured across all omnidirectional hearing aid brands and the open ear canal. These patters reflect the average (within each condition) of all hearing aids used in this study. The output of the hearing aids was measured at 10° increments using two Zwislocki couplers mounted in KEMAR. The output intensity measured from the left and right sides was summed for each measurement azimuth (post hoc) to obtain binaural polar directivity patterns.

of directionality reduces low-frequency gain due to better phase matching for low-frequency components (Borwick, 1990). The fact that the S and SD conditions revealed essentially matched gain indicates that the Widex Senso fitting algorithm includes low-frequency gain restoration after application of directionality. To test the impact of low-frequency gain on the A condition, all subjects were retested at least 2 weeks following initial testing (HINT, condition A, in the reverberant room only). All A condition hearing aid parameters were identical to those used for the initial testing with the exception that low-frequency gain was matched with that provided for each of the subjects by the AD condition. Results revealed an average HINT score of 0.086 for the modified A condition. This score reflects a 0.94-dB improvement in SNR compared to that measured for the A condition before reduction of low-frequency gain and a score that is closer to that measured for the other omnidirectional conditions.

On average, most of the omnidirectional fittings (A, P, and S) resulted in poorer SNR performance (as measured by the HINT) than the unaided condition (see Fig. 3). While there are a number of possible explanations for this difference, the most likely relates to the directionality of the open ear relative to that of an omnidirectional BTE hearing aid. This explanation is supported by polar patterns measured across these conditions (see Fig. 8). These plots reveal that the open ear provides more directionality than the omnidirectional BTE fittings (especially in the higher frequencies). Open-ear directionality is lost due to the microphone placement of BTE hearing aid fittings. These results indirectly support the use of deeper microphone placement (e.g., in the ear, completely in the canal) when fitting omnidirectional hearing aids. The use of deep microphone placement with omnidirectional hearing aids is more directly supported by a recent study revealing the positive impact of deep microphone placement on directionality as measured by real-ear polar patterns (Fortune, 1997).

CONCLUSIONS

1. The BTE directional hearing aids evaluated in this investigation improved SNR in noisy environments, providing wearers with a significant advantage in terms of speech recognition in noise.
2. The similarity in the performance across the directional hearing aids suggested that

the variable processing (e.g., digital vs analog processing and speech detection algorithms) did not affect maximum directional hearing aid performance (either positively or negatively). Alternatively, differences in directivity provided by the directional microphones (across hearing aid types) may have been counteracted by differences in processing, resulting in the measured equivalent performance.

3. Subjects fit with the omnidirectional versions of the Widex and Siemens hearing aids performed slightly better than when fit with the omnidirectional version of Phonak hearing aid. Secondary testing suggests that this may have resulted, in part, from excessive low-frequency gain prescribed by the LoudNorm fitting algorithm used with the Phonak instruments.
4. Measurements obtained in the anechoic chamber not only increased the size of the performance differences seen in the reverberant environment but a different pattern of results was evident as well. These results suggest that data collected in one reverberant environment cannot be used to accurately predict the relative effectiveness of directional microphones in an environment with a different amount of reverberation.
5. Results support previous data suggesting that BTE microphone placement may negatively impact directionality (and speech recognition abilities) relative to the open ear.

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