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Recognition of Speech in Noise with Hearing Aids Using Dual Microphones

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Abstract

Fifty subjects with mild to moderately severe sensorineural hearing loss and prior experience with amplification were evaluated at two sites (25 subjects at each site). Speech recognition in noise scores were measured using the Hearing in Noise Test (HINT) for each subject while wearing binaural behind-the-ear hearing aids allowing switching between two fitting algorithms ("basic" and "party") and two microphone conditions (single microphone omnidirectional and dual-microphone directional). Results revealed an average improvement in signal-to-noise ratio (SNR) of 7.4 to 8.5 dB at the two sites for the directional conditions in comparison to the omnidirectional conditions. No significant improvement in SNR was measured between the two fitting algorithms. In addition, the Profile of Hearing Aid Benefit (PHAB) (Site I) and the Abbreviated Profile of Hearing Aid Benefit (APHAB) (Site II) were administered. Results revealed that the benefit scores for background noise and reduced cues (Site I) and background noise and aversiveness of sounds (Site II) were significantly higher than those reported in the established norms. Finally, 76 percent of the subjects at Site I reported that the experimental hearing aids provided "significantly better" or "better" performance than their current hearing aids.

Key Words: Abbreviated Profile of Hearing Aid Benefit (APHAB), directional microphone, dual microphone, omnidirectional microphone, Profile of Hearing Aid Benefit (PHAB)

Directional microphones have been available in hearing aids for over 20 years. During this time, considerable research has been reported examining the benefits of directional microphones. Several early studies showed an improvement in speech recognition using a directional microphone when speech was presented at 0° azimuth and noise at 180° azimuth (Lentz, 1972; Frank and Gooden, 1973; Sung et al, 1975). Nielson (1973) performed one of the first clinical and field trials comparing hearing aids with omnidirectional and directional microphones. In this study, performance was significantly better with the directional microphone when measured in the sound suite, but the advantage disappeared when the hearing aids were worn in the field.

A number of studies have reported on the limited benefits of directional microphones. Studebaker et al (1980) reported that the advantages of a directional microphone were greatest under anechoic conditions and the advantage decreased as reverberation time increased. Madison and Hawkins (1983), using subjects with normal hearing, reported a directional advantage of 10.7 dB in improved signal-to-noise ratio (SNR) in an anechoic room; the advantage decreased to 3.4 dB under more reverberant conditions (0.6 sec). Hawkins and Yacullo (1984) reported a directional advantage of improved SNRs of 3 to 4 dB for conditions when speech originated from the front and noise originated from the back in rooms with relatively short reverberation times (0.3 and 0.6 sec). This advantage decreased as reverberation increased (1.2 sec) and as speech and noise originated from diffuse fields.

In the past, the directional microphone was a single microphone with a front and rear port, which typically created a 58-μsec delay in the sound reaching the microphone diaphragm from the rear port (Skinner, 1988). Despite the improved SNR provided by hearing aids with directional microphones, Leeuw and Dreschler

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(1991) concluded that, in order for hearing-impaired subjects to realize an improvement in their listening situations, a better directional microphone needed to be developed. In the past several years, a number of microphone designs have been explored to improve directionality. One improvement has been based on array techniques (Bilsen et al, 1993; Kates, 1993; Stadler and Rabinowitz, 1993). One study reported an average improvement in SNR of 7.5 dB using a fixed array directional microphone measured on KEMAR in a diffuse sound field (Soede et al, 1993a). In a follow-up study, Soede et al (1993b) reported an average improvement in speech reception thresholds of approximately 7.0 dB. While these studies report an improvement in directionality in comparison to traditional directional microphones, these microphone arrays require a large spatial separation and have been built only as research prototypes.

Recently, Phonak, Inc. introduced a programmable behind-the-ear (BTE) hearing aid (PiCS Audio-Zoom) that uses a dual-microphone directional microphone. This hearing aid is computer programmable and allows selective use of the dual-microphone array or an omnidirectional microphone via a hand-held remote control. In addition, the user may select from three different electroacoustic settings for distinct listening situations. The "basic" frequency response may be programmed to match the NAL-R prescriptive formula (Byrne and Dillon, 1986) or other fitting formulae, and the two remaining memories may be programmed with "comfort programs" designed to use the directional or omnidirectional microphone for optimal listening in various listening environments.

The primary objectives of the present study were to determine if:

1. Significant differences were present in SNR when the dual microphones of the Audio-Zoom were active in comparison to when only the omnidirectional microphone was active;
2. Significant differences were present in SNR when the dual microphones of the Audio-Zoom were active for the "basic" program in comparison to when the dual microphones were active for the "party" comfort program;
3. Significant differences were present in the mean benefit scores for the subscales of the Profile of Hearing Aid Benefit (PHAB) or Abbreviated Profile of Hearing Aid Benefit (APHAB) for the Audio-Zoom hearing aid in comparison to the mean benefit scores reported for experienced hearing aid users by Cox et al (1991), Cox (1994), and Cox and Alexander (1995); and
4. If subjects reported differences in performance between the Audio-Zoom hearing aids and their current hearing aids after using the Audio-Zoom hearing aids for 30 days.

METHOD

Subjects

Twenty-five adult hearing aid users were included as participants at each of two sites. Site I was the Hearing Laboratory at Washington University School of Medicine in St. Louis, Missouri, and Site II was the Hearing Laboratory at the Mayo Clinic in Rochester, Minnesota. At Site I, there were 13 males and 12 females, with a mean age of 68.2 years and a range from 30 to 82 years. At Site II, there were 14 males and 11 females, with a mean age of 53.2 years and a range from 20 to 83 years. All subjects at Site I had prior experience with binaural amplification (mean years of experience = 5.1 years). At Site II, all subjects had prior experience with amplification (mean years of experience = 5.7 years). Eighteen subjects wore monaural amplification while the remaining seven subjects wore binaural amplification.

Air- and bone-conduction pure-tone thresholds (ANSI, 1989) were measured at 250 to 8000 Hz in the conventional manner (ASHA, 1978), and the results indicated the presence of sensorineural hearing loss. (See Fig. 1 for the mean air-conduction thresholds at Site I [upper panel] and Site II [lower panel]). In addition, immittance audiometry indicated normal middle ear function.

PROCEDURE

Objective Measures

Hearing Aid Fitting

Each subject was evaluated under four different combinations of electroacoustic settings on the hearing aids. These conditions were (1) basic NAL-R frequency response with omnidirectional microphone; (2) basic NAL-R frequency response with dual-microphone directional microphone; (3) "party" frequency response with-omnidirectional microphone; and (4) "party" frequency response with dual-microphone directional microphone. These four conditions were counterbalanced to minimize order effects.

The "party" frequency response is one of many "comfort" programs available on the hearing aid to enhance listening in backgrounds of

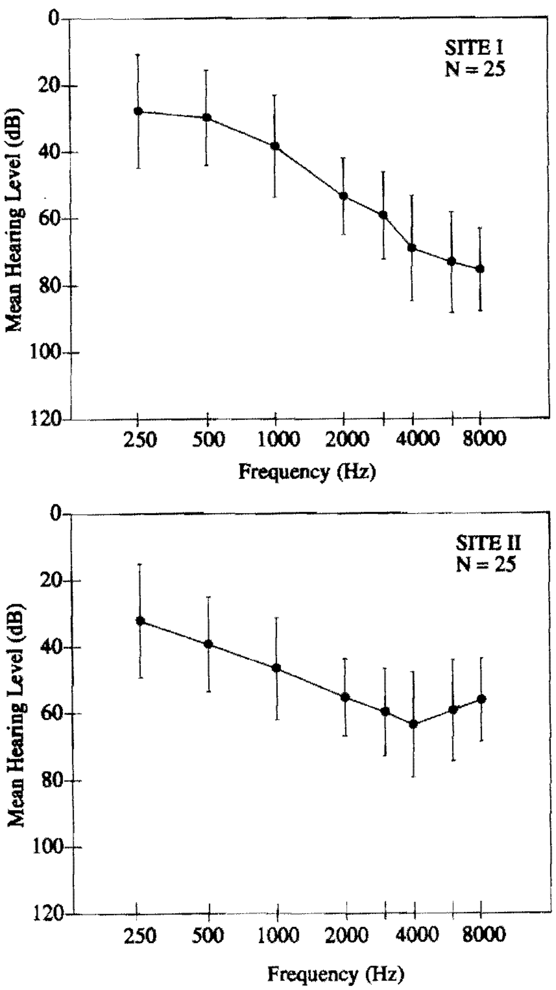

Figure 1 Mean air-conduction thresholds (dB HL) for the 25 subjects at Site I (upper panel) and Site II (lower panel). Also included is ± 1 standard deviation.

various noise sources (Bachler and Vonlanthen, 1994). Each "comfort" program is designed to maximize the articulation index (AI) and/or listening comfort in a target noise source through adjustments of the low-, mid-, and high-frequency gain, SSPL90 setting, overall gain, and compression setting of the hearing aid. In this case, the design of the "party" frequency response assumed a high-intensity, broadband, multibabble noise as the noise source. The specific algorithm for the "party" program, as well as other "comfort" programs, is proprietary.

For each subject, real-ear measurements were made using a Frye 6500 system, to match the real-ear insertion response (REIR) to NAL-R (Byrne and Dillon, 1986) prescribed gain for condition 1 (basic frequency response with omnidirectional microphone). With the probe and reference microphones located in the standard positions and the loudspeaker placed at 0° azimuth, the REIR was matched as closely as possible to the prescribed NAL-R target using a speech-weighted composite noise as the signal. In greater than 80 percent of the 100 ears, the measured REIR came to within 5 dB of the prescribed REIR up to 3000 to 4000 Hz. Subsequently, binaural balance between the two hearing aids was pursued by using the loudness balancing procedure of the PiCS software. For each subject, this completed the fundamental settings for condition 1, upon which the settings for conditions 2 to 4 were based.

Measuring Speech in Noise Using the Hearing in Noise Test

To measure the benefit obtained from the four experimental conditions, the Hearing in Noise Test (HINT) (Nilsson et al, 1991, 1992, 1993) was selected for this study.

The HINT consists of 250 sentences (25 lists of 10 sentences per list) read by a male speaker. The sentences are of approximately equal length (six to eight syllables) and difficulty (first-grade reading level). The HINT estimates the SNR at which the sentences, embedded in noise, can be repeated correctly 50 percent of the time. This type of measure is useful because it enables accurate, reliable estimation of speech recognition in noise for context-rich speech materials. Furthermore, the HINT materials have been digitally recorded for standardized presentation.

In this study, the sentences were presented at 0° azimuth, and the noise, which is temporally and spectrally matched to the sentences, was presented at 180° azimuth. The subject was seated approximately 1.1 meters equidistant from two loudspeakers in an 8′4″ x 9′ (Site I) or 10′ x 8′ (Site II) double-walled sound suite. Neither sound suite was anechoic and reverberation time was not measured. However, Nielsen and Ludvigsen (1978), Studebaker et al (1980), and Madison and Hawkins (1983) report reverberation times of between 0.1 to 0.6 seconds in audiometric sound suites of similar sizes. The sentences and competing noise were presented through a Grason-Stadler 16 (Site I) or Grason-Stadler 10 (Site II) clinical audiometer via a Sony DTC-690 digital audio tape (DAT) deck.

The administration of the HINT requires two lists to be presented (20 sentences) for each experimental condition. The first sentence was presented 10 dB below the attenuator setting necessary for the noise to be presented at

65 dB(A). The first sentence was presented repeatedly, increasing the level of the presentation by 4 dB, until repeated correctly by the subject. Subsequently, the intensity level was decreased by 4 dB and the second sentence presented. Stimulus level was raised (incorrect response) or lowered (correct response) by 4 dB after the subject's responses to the second, third, and fourth sentences. The step size was reduced to 2 dB after the fourth sentence, and a simple up-down stepping rule was continued for the remaining 16 sentences. The calculation of the SNR necessary for 50 percent sentence recognition was based on averaging the presentation levels of sentences 5 through 20, plus the intensity of a twenty-first presentation (used to measure the accuracy of the subject's response).

Upon completing the measurement of the SNR of the HINT test for the four experimental conditions, the basic/omnidirectional program was loaded into Memory 1 of the remote control. The basic/directional program was loaded into Memory 2 and the party/directional program was programmed into Memory 3. Patients were counseled on the use and care of the hearing aids and earmolds and wore the hearing aids for 4 weeks. To obtain a subjective measure of the perceived benefits of the Audio-Zoom hearing aids, the subjects were asked to complete Form B of the Profile of Hearing Aid Benefit (PHAB) at Site I and Form A of the Abbreviated Profile of Hearing Aid Benefit (APHAB) at Site II.

Subjective Evaluation

Profile of Hearing Aid Benefit (Site I)

The PHAB is a subjective assessment scale that reportedly measures perceived benefit from amplification (Cox and Gilmore, 1990; Cox et al, 1991; Cox and Rivera, 1992). It is a 66-item inventory. Each item is a statement, and the subject indicates the proportion of time that the statement is true, using a 7-point scale. The subject responds to each question on the basis of unaided and aided responses. Responses to the unaided segment were obtained prior to the fitting of the hearing aids, while responses to the aided segment were obtained at the end of the trial period. Hearing aid "benefit" (in percent) is defined as the difference between the unaided and aided scores. The PHAB is scored for seven subscales, which include (1) familiar talkers (FT); (2) ease of communication (EC); (3) reverberation (RV); (4) reduced cues (RC); (5) background noise (BN); (6) aversiveness of sounds (AV); and (7) distortion of sounds (DS).

Abbreviated Profile of Hearing Aid Benefit (Site II)

The APHAB is a 24-item inventory modified from the original PHAB (Cox and Alexander, 1995). The APHAB is scored for four subscales, which include (1) ease of communication (EC); (2) reverberation (RV); (3) background noise (BN); and (4) aversiveness of sounds (AV).

Comparison with Present Hearing Aids

In addition, the subjects at Site I were asked to report if they felt that the perceived benefit provided by the Audio-Zoom was (1) significantly better, (2) better, (3) equal to, (4) poorer, or (5) significantly poorer than the perceived benefit of their current hearing aids after they had the opportunity to wear the hearing aids for 30 days.

RESULTS

HINT Scores

Tables 1 and 2 report the individual SNR necessary to achieve 50 percent intelligibility on the HINT test for the four experimental conditions (columns A–D) for Site I and Site II, respectively. Also reported are the improved SNRs for the effects of the directional microphone with the basic frequency response (column B minus column A), the effects of the "party" comfort program (column C minus column A), and combined benefit of the "party" response and the directional microphone over the basic response/omnidirectional microphone (column D minus column A). The bottom of Tables 1 and 2 report the mean, standard deviation, minimum score, and maximum score for each of the conditions. Figure 2 reports the mean and standard deviation in the improved SNR re: the basic response/omnidirectional microphone for Site I (upper panel) and Site II (lower panel).

A one-way repeated measures ANOVA for the results at Site I revealed that significant differences (F = 86.13; df = 3,72; p < .0001) were present across the mean performance for the four experimental conditions. A post-hoc analysis of variance of contrast variables revealed significant differences existed between means for (1) basic/omnidirectional (mean = 0.0 dB) and basic/directional (mean = –7.4 dB) (F = 68.65; df = 1,24; p < .01); (2) basic/omnidirectional (mean = 0.0 dB) and party/directional (mean = –7.7 dB) (F = 66.3; df = 1,24; p < .01), (3) party/omnidirectional (mean = 0.1 dB) and party/directional (mean = –7.7 dB) (F = 103.26; df = 1,24; p < .01); and (4) party/omnidirectional (mean =

Table 1 SNR Necessary to Obtain 50% Intelligibility on the HINT Test for the Four Experimental Conditions (Columns A–D)

	Columns						
Subject	*A Basic Omnidirectional*	*B Basic Directional*	*C Party Omnidirectional*	*D Party Directional*	*B–A Directional Effect*	*C–A Party Effect*	*D–A Combined Effect*
JH	–0.4	–7.6	–8.1	–9.1	–7.2	–7.7	–8.7
WH	0.6	–8.1	–1.3	–7.9	–8.7	–1.9	–8.5
SS	–4.1	–10.2	–2.7	–10.0	–6.1	1.4	–5.9
CD	–0.6	–4.1	1.9	–6.0	–3.5	2.5	–5.4
MH	11.1	–4.1	4.6	–5.1	–15.2	–6.5	–16.2
RA	1.8	–4.5	–0.4	–5.1	–6.3	–2.2	–6.9
DR	–0.8	–7.6	–3.4	–7.9	–6.8	–2.6	–7.1
EN	0.1	–7.9	–0.6	–6.9	–8.0	–0.7	–7.0
LS	8.0	–8.1	13.5	–6.8	–16.1	5.5	–14.8
BA	–3.6	–9.3	–4.6	–9.8	–5.7	–1.0	–6.2
GK	–2.5	–9.3	–1.5	–10.5	–6.8	1.0	–8.0
OL	–3.6	–8.4	–3.6	–10.5	–4.8	0.0	–6.9
AH	–5.3	–9.3	–2.9	–8.8	–4.0	2.4	–3.5
LR	0.6	–4.4	4.4	–4.0	–5.0	3.8	–4.6
MM	–2.7	–8.8	–6.1	–11.6	–6.1	–3.4	–8.9
RW	–4.6	–10.7	–4.4	–9.5	–6.1	0.2	–4.9
HB	9.5	–2.9	14.5	0.8	–12.4	5.0	–8.7
HA	1.1	–7.9	0.1	–10.2	–9.0	–1.0	–11.3
DT	–2.2	–10.0	–5.8	–10.2	–7.8	–3.6	–8.0
EP	8.8	1.3	13.8	2.7	–7.5	5.0	–6.1
EJ	–2.0	–7.2	–2.9	–10.0	–5.2	–0.9	–8.0
MG	–2.9	–8.6	–2.7	–6.5	–5.7	0.2	–3.6
HK	0.1	–7.9	0.6	–8.8	–8.0	0.5	–8.9
JG	–5.5	–10.9	–1.3	–12.4	–5.4	4.2	–6.9
BH	–0.4	–8.1	0.8	–8.8	–7.7	1.2	–8.4
Average	0.0	–7.4	0.1	–7.7	–7.4	0.1	–7.7
SD	4.5	2.8	5.9	3.5	3.0	3.3	2.9
Minimum	–5.5	–10.9	–8.1	–12.4	–3.5	5.5	–3.5
Maximum	11.1	1.3	14.5	2.7	–16.1	–7.7	–16.2

Also provided are the SNRs for the experimental conditions (B–D) relative to the SNR obtained for the basic omnidirectional condition (A) for Site I.

0.1 dB) and basic/directional (mean = –7.4 dB) (F = 68.65; df = 1,24; $p < .01$). The mean differences between the basic/omnidirectional and party/omnidirectional conditions and the basic/directional and party/directional conditions were not significantly different.

A one-way repeated measures ANOVA for the results at Site II revealed that significant differences (F = 66.38; df = 3,72; $p < .0001$) were present across the mean performance for the four experimental conditions. Post-hoc comparisons, using the Tukey honestly significant difference (HSD) method (HSD = 2.11), revealed that significant differences existed between means for (1) basic/omnidirectional (mean = –0.2 dB) and basic/directional (mean = –8.0 dB); (2) basic/omnidirectional (mean = –0.2 dB) and party/directional (mean = –8.8 dB); (3) party/omnidirectional (mean = –0.7 dB) and party/directional (mean = –8.8 dB); and (4) party/omnidirectional (mean = –0.7 dB) and basic/directional (mean = –8.0 dB).

Profile of Hearing Aid Benefit (Site I)

The upper graph in Figure 3 reports the average PHAB benefit scores for the seven subscales. Positive scores suggest benefit from amplification, while a negative score reflects the subject's perception that aided performance was poorer than unaided performance. Paired t-tests on the mean benefit scores reported in Figure 3 revealed that the mean benefit scores for the BN (t-score = 3.97; $p < .01$) and RC (t-score = 2.31; $p < .05$) subscales for the present study were significantly better than the mean benefit scores reported by Cox et al (1991). The paired t-tests for the remaining subscales revealed that the mean differences between the current study and those reported by Cox et al (1991) were not significantly different from each other. These data suggest that the directional microphone used by the Audio-Zoom provided greater benefit in noisy listening environments and in situations with reduced visual cues in comparison

Table 2 SNR Necessary to Obtain 50% Intelligibility on the HINT Test for the Four Experimental Conditions (Columns A–D)

	Columns						
Subject	*A Basic Omnidirectional*	*B Basic Directional*	*C Party Omnidirectional*	*D Party Directional*	*B–A Directional Effect*	*C–A Party Effect*	*D–A Combined Effect*
1	−2.0	−10.0	−3.0	−12.0	−8.0	−1.0	−10.0
2	0.0	−8.0	0.0	−9.0	−8.0	0.0	−9.0
3	−1.7	−10.3	−0.9	−11.1	−8.6	0.8	−9.4
4	−1.0	−10.5	−2.0	−12.0	−9.5	−1.0	−11.0
5	1.0	−9.0	0.0	−11.0	−10.0	−1.0	−12.0
6	−0.4	−8.5	−0.9	−9.4	−8.1	−0.5	−9.0
7	−0.5	−8.0	−0.3	−8.6	−7.5	0.2	−8.1
8	−1.7	−11.2	−1.5	−9.8	−9.5	0.2	−8.1
9	0.8	−8.6	0.1	−9.2	−9.4	−0.7	−10.0
10	0.5	−8.0	0.0	−9.0	−8.5	−0.5	−9.5
11	2.0	−4.0	1.2	−6.8	−6.0	−0.8	−8.8
12	6.0	−5.0	3.1	−5.9	−11.0	−2.9	−11.9
13	4.0	−4.0	3.4	−3.7	−8.0	−0.6	−7.7
14	4.5	−3.5	4.0	−5.0	−8.0	−0.5	−9.5
15	2.2	−3.8	1.8	−4.5	−6.0	−0.4	−6.7
16	0.5	−7.6	1.2	−8.4	−8.1	0.7	−8.9
17	−3.6	−9.9	−3.1	−10.0	−6.3	0.5	−6.4
18	−2.1	−9.3	−3.1	−9.3	−7.2	−1.0	−7.2
19	−4.5	−10.4	−4.6	−11.1	−5.9	−0.1	−6.6
20	0.1	−7.1	−0.1	−8.6	−7.2	−0.2	−8.7
21	−2.1	−8.9	−1.1	−8.9	−6.8	1.0	−6.8
22	1.0	−7.1	0.1	−7.1	−8.1	−0.9	−8.1
23	−1.1	−8.1	0.0	−8.1	−7.0	1.1	−7.0
24	−5.6	−10.7	−6.6	−11.1	−5.1	−1.0	−5.5
25	−2.2	−8.9	−4.1	−9.1	−6.7	−1.9	−6.9
Average	−0.2	−8.0	−0.7	−8.8	−7.8	−0.4	−8.5
SD	2.7	2.3	2.5	2.2	1.4	0.9	1.7
Minimum	−5.6	−11.2	−6.6	−12.0	−5.1	1.1	−5.5
Maximum	6.0	−3.5	4.0	−3.7	−11.0	−2.9	−12.0

Also provided are the SNRs for the experimental conditions (B–D) relative to the SNR obtained for the basic omnidirectional condition (A) for Site II.

to the benefits reported by experienced users of linear amplification (Cox et al, 1991; Cox, 1994).

Abbreviated Profile of Hearing Aid Benefit (Site II)

The lower graph in Figure 3 reports the average APHAB benefit scores for the four subscales of the APHAB for Site II. Paired t-tests on the mean benefit scores reported in Figure 3 revealed that the mean benefit scores for the BN (t-score = 2.65; $p < .01$) and AV (t-score = 2.22; $p < .05$) subscales were significantly better than the mean benefit scores reported by Cox (1994) and Cox and Alexander (1995) for experienced users of linear amplification. These data suggest that the directional microphone used by the Audio-Zoom provided substantial benefit in noisy listening situations, and also fared better (on average) than linear (peak clipping) amplification for preventing aversive sounds from becoming uncomfortable.

Comparison with Current Hearing Aids (Site I)

Table 3 reports the responses to the question that asked the 25 subjects at Site I to report on their perceived benefit of the dual-microphone responses of the Audio-Zoom (Memory 2 or 3) in comparison to their current hearing aids at the conclusion of the 30-day trial period. It is important to note that the hearing aids reported in Table 3 were fit by two of the authors (MV or LP) and are known to be fitted appropriately.

One subject (JH) reported that the performance of the Audio-Zoom was significantly poorer in performance than her current hearing aids. Five subjects (CD, MH, EN, MM, and HB) reported that the performance of the Audio-Zoom was equivalent in performance to their current hearing aids. However, two of these subjects (EN and MM) reported that the Audio-Zoom was equivalent to their present hearing aids in "quiet," but superior in "noise." Twelve subjects (SS, RA,

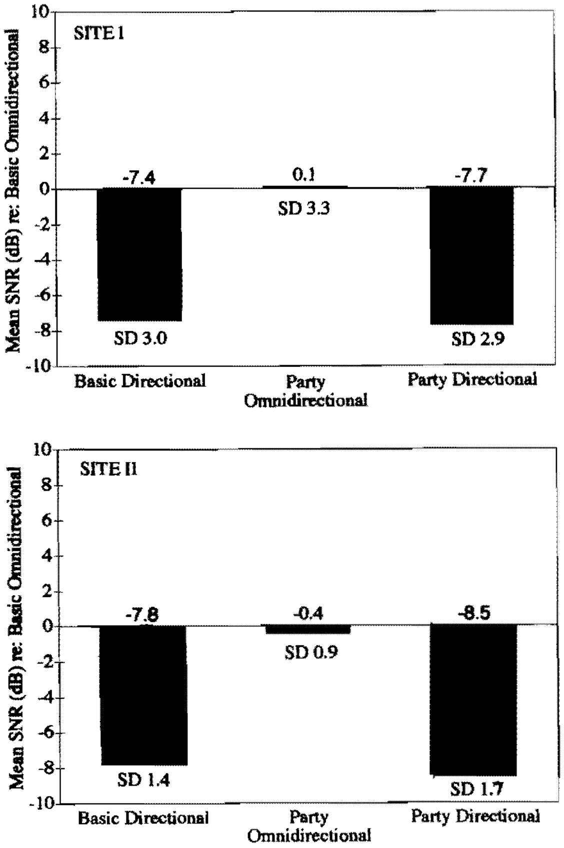

Figure 2 Mean and standard deviation of the improved SNR for the three experimental conditions re: the basic frequency response/omnidirectional microphone. The upper panel reports the results from Site I and the lower panel reports the results from Site II.

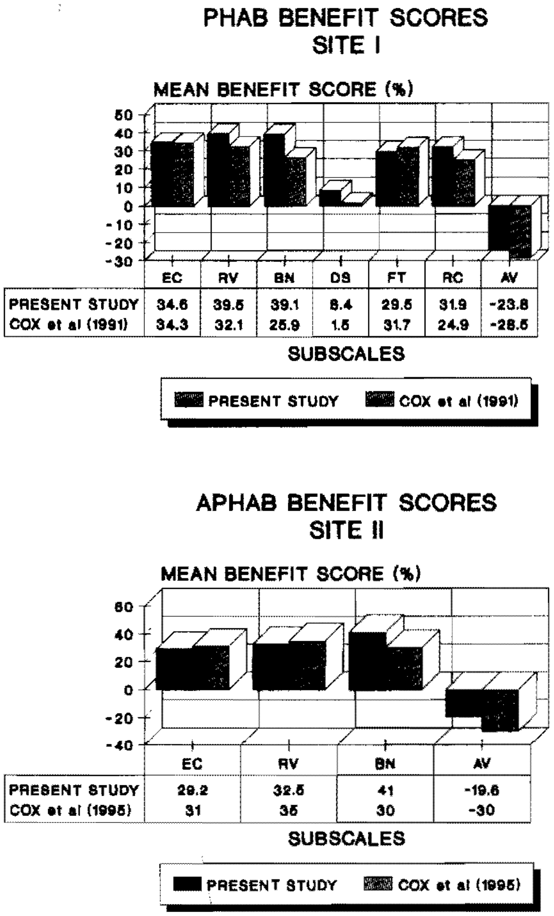

Figure 3 Mean benefit scores for the PHAB (upper graph) and APHAB (lower graph) for Sites I and II. Also included are the mean benefit scores reported for the PHAB (Cox et al, 1991) and APHAB (Cox and Alexander, 1995).

BA, OL, AH, RW, HA, EJ, MG, HK, JG, and BH) reported that the performance of the Audio-Zoom was better than the performance of their current hearing aids. Once again, three subjects (SS, BA, and AH) remarked on the superior performance of the Audio-Zoom in "noisy" listening situations. Finally, seven subjects (WH, DR, LS, GK, LR, DT, and EP) reported that the performance of the Audio-Zoom was significantly better than the performance of their current hearing aids. Many subjects remarked that the performance of the Audio-Zoom was equal to the performance of their current hearing aids in "quiet," but was superior in "noise." In fact, 19 subjects (76%) reported that the performance of the Audio-Zoom was "better" or "significantly better" than their current hearing aids. In addition, two subjects reported that the performance of the Audio-Zoom was equal in "quiet," but "significantly better" in noise in comparison to their current hearing aids. Thus, a total of 21 subjects (84%) reported that the Audio-Zoom provided either "better" or "significantly better" performance than their current hearing aids. This was found to be significant ($p < .01$) using a binomial test (SPSS, 1988).

DISCUSSION

The average improvement reported in this study (7.4 to 7.7 dB for Site I and 7.8 to 8.5 dB for Site II) is nearly double the 3 to 4 dB improvement in SNR reported by Madison and Hawkins (1983) and Hawkins and Yacullo (1984) when using a single directional microphone with front and rear ports. There are several reasons that may account for the significant improvement in SNR reported in this study when compared to the results reported in the past. First, the effectiveness of a directional microphone is determined, in part, by the difference in amplification between the front (0°) and the back (180°). This is referred to as the front-to-back ratio (FBR), and increased attenuation of the noise source from the back results in improved noise

Table 3 Responses to a Question at Site I Comparing the Performance of the Audio-Zoom to Subjects' Current Hearing Aids

Subject	*Hearing Aids*	*Answer*				
		A	*B*	*C*	*D*	*E*
JH	ReSound BT2				X	
WH	Trilogy I (Linear)	X				
SS	Resolution (KP = 55)		X			
CD	Intra 5 (Linear)			X		
MH	Trilogy II (KP = 60)			X		
RA	CE-9 (Linear)		X			
DR	ReSound BT2	X				
EN	CE-8 (Linear)			X		
LS	CE-9 (Linear)	X				
BA	ReSound BT2		X			
GK	CE-9 (Linear)	X				
OL	Tympanette (Linear)		X			
AH	ReSound BT2		X			
LR	ReSound BT2	X				
MM	ReSound BT2			X		
RW	Tympanette (Linear)		X			
HB	R = Unitron 905 (Linear) L = CE-8 (Linear)			X		
HA	Intra 5 (Linear)		X			
DT	Intra 5 (Linear)	X				
EP	CE-8 (Linear)	X				
EJ	CE-8 (Linear)		X			
MG	Intra 5 (Linear)		X			
HK	R = Bernafon T86 (Linear) L = Starkey 163 (Linear)		X			
JG	3M Memorymate		X			
BH	Tympanettes (Linear)		X			
Total		7	12	5	1	0

A = significantly better; B = better; C = no significant difference; D = poorer; E = significantly poorer.

suppression. The FBR for the directional microphone used in the Madison and Hawkins (1983) study revealed FBRs of approximately 8, 13, 12, 10, and 2 dB at 500, 1000, 2000, 3000, and 4000 Hz, respectively. The FBR for the dual microphones used in the present study is reported by the manufacturer to be approximately 27, 20, 20, 20, and 12 dB for the same frequencies. Clearly, the FBRs for the dual microphone provides significantly greater attenuation of signals arriving from the rear. In addition, the effectiveness of the dual microphone extends to a broader frequency range than the directional microphone used in the Madison and Hawkins (1983) study. Mueller and Johnson (1979) reported improved speech recognition in noise for the Synthetic Sentence Identification (SSI) Test as the FBR reported at 1000 Hz was increased from 6 to 20 dB. Along the same line, the experimental hearing aid is reported to possess higher directivity (Bachler, personal communication). The Directivity Index (DI), measured across frequency and expressed in dB, is a way to measure the directional properties of an acoustic system (e.g., ear canal, microphone, etc.) in a diffuse field. When applied to hearing aid microphone systems, the DI can be taken as the amount of attenuation that the hearing aid microphone system achieves in the diffuse sound field over that achieved with an omnidirectional microphone in a BTE case worn over the ear of a mannequin. A DI of 0 dB would suggest that the hearing aid microphone system achieves the same extent of attenuation as an omnidirectional microphone worn over the ear. The higher the DI, the more directional the hearing aid microphone system. Well-designed directional microphones yield a DI of approximately 2 to 3 dB up to 2000 Hz and 0 dB at 4000 Hz. The experimental hearing aid yielded a DI of 4 dB up to 2000 Hz and 2.5 dB at 4000 Hz (Bachler, personal communication). These differences may account for the higher SNR reported in this study.

The type of material used in this study was different from that of Madison and Hawkins (1983) and Hawkins and Yacullo (1984). This study used sentence material as the stimulus, whereas the other two studies used the NU-6 monosyllabic word lists. Meaningful sentence material used in the HINT, because of its rich, contextual cues, may allow easier identification and yield a steeper slope on the performance-intensity (P-I) function than monosyllabic words. This suggests that for a given value of SNR enhancement, the percentage change in intelligibility may be higher for sentence materials than for monosyllabic words. It does not suggest, however, that the magnitude of SNR improvement seen in this study would decrease if monosyllabic words were used instead. Considering that daily speech communication occurs in a context-rich environment, the choice of sentence materials in this study may reflect more closely the real-world potential benefit of this directional microphone system in optimal noisy situations.

The results reported in Tables 1 and 2 and Figure 2 reveal that the addition of the dual microphone provided significant improvements for both the basic and party frequency responses, in terms of SNRs, by an average of 7.4 to 8.5 dB at Sites I and II, respectively (columns B–A and D–A). The improvement was as little as 3.5 dB and as great as 16.1 dB across the 50 subjects. Soli and Nilsson (1994) reported that an improvement by 1 dB could lead to an improvement in speech recognition scores of 8.5 percent on the HINT. Although it is tempting to speculate that the observed SNR improvement could lead to 62 percent to 72 percent improvement in sentence intelligibility, it needs to be pointed out that the normative conditions used in the Soli and Nilsson (1994) study are different from the present study. Soli and Nilsson (1994) presented a binaural noise source at 45° on each side of the subject, while, in the present study, a single noise source was presented at 180°. Assuming that the single noise source is a less difficult listening situation than the binaural noise source, the slope of the P-I function obtained with the single noise source will be steeper than that reported for the binaural noise source. If this is a correct assumption, one would expect that the percent improvement in sentence intelligibility may exceed the 63 percent to 72 percent calculated with the 8.5 percent/dB slope factor. Obviously, the calculation assumes that the differences are measured along the monotonic portion of the P-I function of the sentences of the HINT, and that the same P-I function can be used for normal and hearing-impaired listeners. In addition, it must be pointed out that hearing-impaired listeners may show less change in sentence intelligibility than normal-hearing listeners.

Finally, post-hoc analysis at Sites I and II indicated that the addition of the party frequency response versus the basic frequency response did not result in significant enhancement of the SNR. This finding may not be surprising if the "party" algorithm merely reduces gain in different frequency regions. The same changes would reduce both the signal and noise in equal amounts and, therefore, no improvement in the SNR would be seen. Perhaps a different finding may result if (a) different stimuli were used; (b) the stimuli were presented at a higher intensity level more appropriate for the "party" algorithm, or (c) the dependent variable were something other than SNR (i.e., speech intelligibility for monosyllabic word lists embedded in multitalker babble, sound quality judgments, or speech intelligibility ratings). A separate evaluation of these algorithms is warranted before a conclusion on their effectiveness can be made. Interestingly, this finding mirrors the results reported for single-microphone adaptive frequency response hearing aids reported in the literature (Van Tasell et al, 1988; Klein, 1989; Tyler and Kuk, 1989; Fabry, 1991).

CONCLUSIONS

Fifty subjects were evaluated with the Phonak Audio-Zoom under four experimental conditions at two sites. The major findings of this project showed that:

1. Use of the dual microphone of the Audio-Zoom improved the SNR necessary to achieve 50 percent intelligibility of sentences in noise by an average of 7.4 to 7.7 dB (Site I) and 7.8 to 8.5 dB (Site II) relative to the condition where the omnidirectional microphone was active and the frequency/gain response "matched" the prescribed NAL-R. These results, however, must be tempered by the fact that they represent optimal environment for directional microphones: a sound suite with low levels of reverberation and with speech and noise originating from separate loudspeakers positioned at ideal locations. The effects of reverberation and diffuse speech and noise will undoubtedly degrade the magnitude of the effect.
2. The "party" frequency response, under the present experimental design, did not significantly improve the mean SNR.
3. The magnitude of the PHAB benefit scores for two subscales (BN, RC) were statistically greater than the mean benefit reported by Cox et al (1991) for users of linear amplification. The magnitude of the APHAB benefit scores for two subscales (BN, AV) were statistically greater than the mean benefit reported by Cox and Alexander (1995) for users of linear amplification. For the other subscales of either the PHAB or APHAB, there were no significant differences between the present data and the data reported by Cox et al (1991) for the PHAB or Cox and Alexander (1995) for the APHAB.
4. The subjects at Site I reported a general preference for the Audio-Zoom when asked to compare the performance of the Audio-Zoom to the performance of their current hearing aids. This finding was present for users of both linear and nonlinear hearing aids.

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