Comparison of Benefits Provided by Different Hearing Aid Technologies

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Abstract

The performance of 40 hearing-impaired adults with the GN ReSound digital BZ5 hearing instrument was compared with performance with linear hearing aids with input compression limiting (AGC-I) or two-channel analog wide dynamic range compression (WDRC) instruments. The BZ5 was evaluated with an omnidirectional microphone, dual-microphone directionality, and a noise reduction circuit in combination with dual-microphone directionality. Participants were experienced hearing aid users who were wearing linear AGC-I or analog WDRC instruments at the time of enrolment. Performance was assessed using the Connected Speech Test (CST) presented at several presentation levels and under various conditions of signal degradation and by the Profile of Hearing Aid Benefit (PHAB). Subjective ratings of speech understanding, listening comfort, and sound quality/naturalness were also obtained using 11-point interval scales. Small performance advantages were observed for WDRC over linear AGC-I, although WDRC did not have to be implemented digitally for these performance advantages to be realized. Substantial performance advantages for the dual microphones over the omnidirectional microphone were observed in the CST results in noise, but participants generally did not perceive these large advantages in everyday listening. The noise reduction circuit provided improved listening comfort but little change in speech understanding.

Key Words: Benefit, digital, directionality, dual microphones, GN ReSound BZ5 hearing instrument, hearing aids, linear, noise reduction, wide dynamic range compression

Technological advancements have resulted in a number of new signal processing schemes being introduced into hearing aids over the past several years. Among these new technologies are wide dynamic range nonlinear amplifiers, multi-channel devices, fully digital systems, and special features such as noise reduction (NR) algorithms and dual-microphone directionality.

Although traditional linear amplifiers continue to be fit frequently to hearing-impaired patients, clinicians have a variety of alternatives...
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available. As expected, the newer, more complex, signal-processing circuits are more costly. Hence, patients and practitioners must decide if the benefits provided by the new technology justify the added expense. Inevitably, this is an individual decision. Ideally, it should be based on clinical data regarding the efficacy of various signal-processing schemes for patients with similar hearing impairments.

The major focus of fitting a hearing aid to a hearing-impaired patient is to maximize performance and benefit in everyday living. What is needed, therefore, is a dependent measure or set of measures that reflect (i.e., predict) hearing aid performance and benefit in everyday use. Unfortunately, there is no consensus among clinical researchers regarding how best to represent hearing aid performance and benefit in everyday living (e.g., Walden, 1997; Byrne, 1998). Clearly, there are a number of factors affecting hearing aid benefit that may interact in complex ways to determine how much benefit a particular patient will receive with a particular hearing aid (Walden, 1998).

Walden et al (1984) suggested that hearing aid performance and benefit can be assessed in four fundamentally different everyday listening situations, hereafter referred to as prototype listening situations (PLSs) (see Walden, 1997, for a more complete discussion). The first (PLS1) involves listening to soft speech in relative quiet (QT), typically in close proximity to the talker. The second (PLS2) includes listening situations with reduced cues, such as reverberant speech or speech spoken at a distance and/or without the benefit of visual cues. The third (PLS3) involves listening to speech in background noise. The last PLS (PLS4) is different from the first three in that it does not involve speech understanding, per se, but rather listening to environmental sounds. This could include aversive noises, music, the sounds of nature, and voice quality. In the absence of a measure of hearing aid benefit in everyday listening known to have high predictive validity, we have attempted to represent hearing aid performance in each of these PLSs when assessing benefit (Walden et al, 1998, 1999).

The purpose of this study was to compare the benefit that hearing-impaired patients received from a variety of hearing aid technologies in each of the four PLSs described above. Additional control conditions include comparing different hearing aid technologies with unaided (UA) performance measures and with the performance of persons with normal hearing (NH).

**METHOD**

The results reported here are based on a manufacturer-sponsored clinical trial of the GN ReSound BZ5 hearing instrument (hereafter, BZ5). The purpose of this clinical trial was to assess user benefit with this open-platform digital system. A more complete description of the device is provided below.

**Subjects**

Participants were older adults with gradually sloping moderate sensorineural hearing loss and relatively good residual speech recognition ability who were regular and generally satisfied users of analog hearing aid technology. The selection criteria required that participants have acquired bilateral sensorineural hearing losses of 10 to 60 dB HL from 500 to 1000 Hz and 30 to 85 dB HL from 1000 to 6000 Hz. No interaural difference could exceed 20 dB from 500 to 6000 Hz. Additionally, participants were required to have normal (Type A) tympanograms and normal ipsilateral acoustic reflexes at 1000 Hz. All participants had to be binaural hearing aid users who wore their instruments a minimum of 4 hours per day. Their hearing aids had to be in good working order and either linear Class D instruments with input compression limiting or analog two-channel wide dynamic range compression (WDRC) devices.

Forty adult males meeting these criteria were recruited from the patient population of the Army Audiology and Speech Center. Their mean age was 67.8 years (SD = 6.3 years; range = 52–76 years). The mean audiogram is shown in Figure 1. The average Northwestern University Auditory Test No. 6 (NU-6) score (presented monitored live voice in quiet at a comfortable presentation level) was 84.0 percent (SD = 9.6; range = 60–100) in the right ear and 80.7 percent (SD = 9.8; range = 56–100) in the left ear. The mean years of hearing aid use prior to participation in the study was 9.4 years (SD = 6.5; range = 2–30). Twenty-one of the 40 participants wore binaural linear automatic gain control with input compression limiting (AGC-I) hearing aids (hereafter, LINAGC) at the time of enrollment and 19 wore binaural digitally programmable analog two-channel WDRC hearing aids (hereafter, WDRCANLG). Participants had been fit with the LINAGC or WDRCANLG hearing aids a minimum of 1 year and not more than 3 years prior to enrollment in the study.

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Hearing Aids

The BZ5 is a behind-the-ear (BTE), open-platform fully digital instrument with variable compression ratios in 14 overlapping bands and four memories (programming configurations). The syllabic compression threshold is ≤ 45 dB SPL, with the compression ratio ranging from 1.0 to 3.0 (program dependent in each band). The attack time is ≤ 5 msec, and the release time is 70 msec (120 msec at 250 Hz). The input limiting threshold is 75 to 100 dB SPL (program dependent in each band) with a > 15.0 compression ratio and ≤ 5-msec attack and 70-msec release times. Six “handles” are provided for programming the gain parameters. For the participants in this study, the mean compression ratios (range in parentheses) for the six handles from low- to high-frequency bands were 1.2 (1000–1600 Hz), 1.2 (1100–1600 Hz), 1.7 (1200–2300 Hz), 2.0 (1400–3000 Hz), 2.2 (1500–3000 Hz), and 2.0 (1000–3000 Hz). The right and left ear fittings have been combined here because the means between the two were < 0.1 for each handle. In addition to multiband fast-acting WDRC, the BZ5 includes optional microphone directionality and NR sound processing. Directionality is achieved electronically on the BZ5 via a two-microphone system and is selectable among hypercardioid, cardioid, and bidirectional polar patterns; however, the (default) hypercardioid pattern was used throughout the study. Moderate low-frequency gain is introduced when the dual microphones are activated to compensate partially for the normal 6 dB per octave roll-off associated with directionality. GN ReSound’s NR circuit detects intensity modulations in 14 frequency bands and attenuates the output of a given band in inverse proportion to the extent of the modulations detected. The algorithm assumes that level fluctuations within a band reflect the presence of speech. Where intensity modulations are minimal, such as for relatively steady environmental noises and multitalker babble, maximum attenuation is introduced. As a result, overall output can be reduced by as much 7.5 dB when the NR circuit is activated.

Following the manufacturer’s recommendations, the BZ5 was coupled to the participant’s ears with custom, lucite earmolds, standard #13 tubing, and appropriate venting (typically, medium or small). ReSource II, Version 1.2, software with audiometric threshold data was used to program the instruments.

The LINaGc hearing aids were custom half-shell instruments with standard volume wheels, typically manufactured by Danavox (Mentonka, MN). They had been fitted using the National Acoustic Laboratories-Revised (NAL-R) insertion gain targets with a 60 dB SPL input level. The same measurements were repeated at the time of recruitment into the BZ5 study to verify that the hearing aids were working properly. No differences greater than 5 dB for the test frequencies 500 to 4000 Hz were noted between the measurements made at the time of the original fitting and those made at the time of enrolment.

None of the LINaGc users had participated in previous clinical trials. In contrast, 17 of the 19 people who were using two-channel WDRCaNw instruments at the time of enrolment in the BZ5 study had participated in earlier studies (Walden et al, 1998, 1999). Each had opted at the conclusion of the earlier trials to purchase the WDRCaNw instruments to replace linear hearing aids. Of the 19 participants in the WDRCaNw group, 8 were wearing BTE instruments (GN ReSound Model BT2), 1 was wearing a
Table 1 Summary of the Dependent Measures for Each of the Four Prototype Listening Situations

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<tr>
<th>PLS</th>
<th>Laboratory Measures (CST)</th>
<th>Subjective Field Ratings (PHAB)</th>
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<tr>
<td>1</td>
<td>Listening in quiet</td>
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<td></td>
<td>Speech level = 50 dBA</td>
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<td>Six-talker babble = 40 dBA</td>
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<td>2</td>
<td>Listening in reverberation</td>
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<td>Speech level = 60 dBA</td>
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<td>Reverberation time = 0.78 sec</td>
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<td>3</td>
<td>Listening in noise</td>
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<td></td>
<td>Speech level = 60 dBA</td>
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<td>Two-talker babble = 60 dBA</td>
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<td></td>
<td>Speech level = 75 dBA</td>
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<td>Six-talker babble = 73 dBA</td>
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Dependent Measures

Hearing aid performance and benefit were assessed using a protocol similar to that used in earlier hearing aid clinical trials (Walden et al, 1998, 1999), which includes laboratory measures of speech recognition and subjective field ratings designed to measure benefit under each of the four PLSs. In addition, several subjective ratings of speech understanding, comfort, and quality/naturalness were obtained for each of the experimental conditions of the BZ5.

Laboratory Measures of Speech Recognition

The Connected Speech Test (CST) (Cox et al, 1987, 1988), using different presentation levels and levels of background speech babble or reverberation (REV), was used to measure UA and aided speech recognition. These dependent measures are summarized in the left column of Table 1. Presentation levels and signal-to-noise ratios (S/N) were selected to yield mid-range scores and to be representative of listening situations that are encountered in everyday listening (Walden, 1997). Both the test sentences and competing babble were digitized and presented on line to the listeners. Note that there was one test condition each to represent PLS1 and PLS2, two test conditions to represent PLS3, and no laboratory test of PLS4, which was evaluated only through field ratings.

All laboratory measures were obtained in a 3.1 m x 2.4 m audiometric test booth. A loudspeaker was mounted at ear level for a seated listener, 0.25 m from the wall surface and at the midpoint on all four walls. For the three CST
conditions that involved a competing multitalker babble, the test sentences were presented from a loudspeaker positioned at 0° azimuth and the same competing babble was presented simultaneously (“correlated”) through the three loudspeakers positioned at 90°, 180°, and 270° azimuth. The overall sound pressure levels of the signal and noise were checked daily, and the frequency response of each speaker was checked weekly. Because the level of the signal arriving from each loudspeaker was quite sensitive to small changes in location within the test space, a dental headrest was attached to the listener’s chair to keep the head in a fixed position during testing. The participant’s head position was also monitored visually by the tester throughout the administration of the laboratory measures. For the REV condition, the CST sentences were presented from the front speaker in quiet. The sentences were digitally processed to simulate a REV time of 0.78 sec (Peterson, 1986). Four CST passages were presented per test condition, so test scores were based on correct identification of 100 key words.

All four laboratory test conditions were administered both UA and for the BZ5OMNI programming configuration. For the BZ5DR and BZ5DR+NR programs, however, only the two speech-in-noise test conditions (PLS3) were administered based on an a priori assumption that the directionality and NR features would be of little additional benefit (over the BZ5OMNI program) in relative quiet (+10 S/N) and under conditions of simulated REV from a single loudspeaker.

Two modifications were made to the standard commercially available recordings of the CST sentences and competing multitalker babble. First, a brief noise ramp was inserted before and after each test sentence to avoid an abrupt simultaneous onset and offset of sentence and noise. Second, for the moderate noise test condition (60 dBA, 0 S/N), the sentences were presented with a two-talker competing babble rather than the standard six-talker babble. The rationale for this change was an assumption that everyday noisy listening situations with a talker speaking at a moderate level typically involve one or two competing voices rather than a din of competing voices. Although this change in the background babble was considered important to improve the validity of the moderate noise test condition, it created a potential testing problem in that silent “holes” in the noise occurred because there were only two talkers.

If the test sentences and two-talker babble were recorded in synchrony, as in the commercially available recordings with the six-talker babble, key words that occurred during a silent interval in the noise would be consistently audible. In order to address this problem, a 5-minute recording of the two-talker babble was digitized and sampled randomly for presentation with each test sentence, thereby positioning the silent intervals randomly in relation to the key words.

**Subjective Field Ratings**

The Profile of Hearing Aid Benefit (PHAB) (Cox and Gilmore, 1990; Cox and Rivera, 1992) was used to assess hearing aid performance and benefit in everyday listening situations. The four scales of the PHAB represent benefit in each of the four PLSs. The four scales are further divided into seven subscales, shown in the right column of Table 1. Following the trial with the BZ5, the PHAB was administered only once, that is, it was not administered separately for each experimental condition of the BZ5. Rather, participants were instructed to consider each item on the questionnaire and rate aided performance according to which of the three programming configurations of the BZ5 (BZ5OMNI, BZ5DR, BZ5DR+NR) would work best in that listening situation.

**Field Ratings for Each BZ5 Program**

Subjective field ratings for each of the three BZ5 programming configurations were obtained using 11-point semantic differential scales. Ratings were obtained for three conditions of speech understanding, two conditions of sound comfort, and two conditions of sound quality/naturalness. The seven ratings summarized in Figure 2 were obtained for each of the three BZ5 configurations for a total of 21 separate ratings.

**Procedures**

Participation in this clinical trial consisted of five test sessions. The hearing aid fittings and testing procedures are summarized here. A more detailed description of the procedures is provided in Walden et al (1998).

**Session 1**

Basic audiometric testing was conducted to ensure that the participant met the selection cri-
Field Ratings for Each Program
(OMNI, DR, DR+NR)

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- Speech Understanding (0 = very poor, 10 = very good)
  - Quiet
  - Reverberation
- Background noise
- Sound Comfort (0 = very uncomfortable, 10 = very comfortable)
  - Nonspeech sounds (e.g., warning sounds, traffic noise)
  - Speech in background noise
- Quality and Naturalness of Sound (0 = very unpleasant, 10 = very pleasant)
  - Sounds of nature, music, people's voices
  - Speech in background noise

Figure 2 Field ratings obtained for each programming configuration. Three dimensions of speech understanding, two dimensions of sound comfort, and two dimensions of sound quality/naturalness were evaluated for each of the three BZ5 programming configurations (memories) using 11-point scales.

Session 2 (1–2 Weeks Post-Enrolment)

During the second visit, the CST was administered to the participants under the four test conditions described in the left column of Table 1. These four conditions were administered both UA and with the participants wearing their own LINAGC or WDRCANLG hearing aids. The order of testing for the eight CST measures was randomized across participants. Several practice sentences were presented to familiarize the participant with each CST condition and, in the case of the LINAGC users, to permit volume adjustments prior to the administration of each test.

Session 3 (5–7 Months Post-Enrolment)

Due to an unanticipated delay in receiving the BZ5 instruments from the manufacturer, several months intervened between sessions 2 and 3. Pure-tone testing was repeated to ensure that participants still met the audiometric selection criteria and to provide current thresholds for programming the instruments. Virtually all threshold differences observed between sessions 1 and 3 were within test–retest limits. During the third session, the participants were fitted with the BZ5 binaurally using ReSource software Version 1.1.2. The BZ5 has four programmable memories with software options designed for specific types of listening environments, such as music, a restaurant, or a party. The first (default) program (memory 1) for all participants was the basic speech program with the omnidirectional microphone (BZ5_OMNI). Modifications to this program were made, if needed, using the manufacturer's troubleshooting guide for fine-tuning based on the user's impressions at the time of fitting and, again, after an initial 2- to 3-week adjustment period (see below). In general, the adjustments were minor and infrequent. The second and third programs (memories) had the same gain and compression ratios across frequency bands as the basic speech program; however, the dual-microphone feature (default setting: hypercardioid with moderate boost) was engaged for one of the programs (BZ5_DR), and the dual microphones and the moderate (default) NR features were activated for the other program (BZ5_DR_NR). The assignment of these programs to memories 2 and 3 was counterbalanced across the participants. If the default program (memory 1) was modified during the initial adjustment period, the changes were extended to these other two speech programs. The fourth memory was programmed for telephone use but was not explicitly evaluated in this study. After brief practice, participants became adept at switching from one program to another via a push-button on the back of the instrument, aided by an audible set of tones that indicated which program had been activated. No other user-operated controls were provided.

In addition to the above features, the BZ5 has a digital feedback suppression (DFS) circuit that can be activated, if needed, at the discretion of the audiologist. This was engaged for 8 of the 40 subjects in this clinical trial. In these cases, the DFS was disengaged for the test box electroacoustic measurements. Real-ear measurements were not obtained for the 8 participants where DFS was employed.

The participants were given a sheet reminding them that memories 1 to 3 were speech programs and memory 4 was for telephone use only. The specific differences between the three speech programs were not discussed, other than indi-
eating that speech was processed differently. The participants were instructed to scan through memories 1 to 3 periodically, particularly when they changed listening environments, and note which memory provided the best hearing in a given situation. They were also told that both instruments (i.e., right and left ears) were to be set in the same memory. Participants were given copies of the 11-point rating scales that were used later in data collection to guide their assessment of the performance of the three programs in everyday listening situations, although they were instructed not to fill them out during the trial period. At the end of session 3, participants were scheduled for a finetuning session 2 to 3 weeks later.

**Session 4 (2–3 Weeks Following Session 3)**

During the fourth visit, participants reported on their experiences with the BZ5, and any final adjustments that appeared necessary were made. Once the fittings were finalized, real-ear and 2-cc coupler gain measures were obtained on each instrument for composite noise signals with 50, 65, and 80 dB SPL input levels. At the end of the fourth visit, participants were sent out for a 30- to 45-day trial with the BZ5.

**Session 5 (4–6 Weeks Following Session 4)**

During the final session, the PHAB was administered to assess (overall) BZ5 subjective benefit. The UA and BZ5-aided ratings were obtained without the participant having access to the UA and aided (participant’s own hearing aids) PHAB ratings obtained during session 1. Next, the seven 11-point rating scales for evaluating each of the three speech programs (BZ5 OMNI, BZ5 DR, BZ5 DR+NR) were administered. Following the subjective measures, the laboratory tests were administered both UA and with the participant wearing the BZ5. Prior to the CST data collection, the instruments were reprogrammed to change memory assignments. The same assignments were used for each participant (memory 1 = BZ5 DR+NR, memory 2 = BZ5 DR, memory 3 = BZ5 OMNI) and differed from those used during the trial period. The patients were informed that the memory assignments, but not the programs themselves, had been changed for testing purposes. This reprogramming was done to reduce potential subject bias and the chance for investigator errors in hearing aid settings during testing.

**RESULTS**

**Real-Ear and 2-cc Coupler Measurements**

Figure 3 shows the average 2-cc coupler gain of the basic speech program (BZ5 OMNI) for each ear (solid lines). In addition, gain curves for the BZ5 programmed for the mean right- and left-ear audiograms of the 40 subjects (see Fig. 1) are shown (dashed lines). It is apparent that there were no systematic deviations from the basic fitting algorithm during the initial period of adjustments.

The fitting algorithm for the BZ5 is proprietary, but the gain curves can be compared to known target formulae. Figure 4 shows the coupler gain of the BZ5 fittings (solid lines) in relation to the NAL-R prescribed 2-cc coupler
gain (Byrne and Dillon, 1986) for the mean pure-tone thresholds of the participants (the 15-dB reserve gain has been subtracted). Although there are some deviations in the low- and mid-frequency regions, the 65-dB response curve for the BZ5 is the best overall match to the NAL-R target. Real-ear insertion gain was measured with speech-weighted composite signals at three input levels (50, 65, and 80 dB SPL) for the participants' own hearing aids (either LIN, or WDRC) and for the 32 fittings of the BZ5 (basic speech program) for which the FC had not been used. The volume settings of the WDRC instruments were as programmed. The volume for the LIN hearing aids was set by the participant to the level that he typically used in everyday conversational listening environments. Figure 5 compares insertion gain, for a 65 dB SPL input signal, of the participants' own hearing aids to that of the BZ5. The gain characteristics between the participants' own hearing aids and the trial instruments were similar for this input level, except in the high-frequency region, where the BZ5 instruments provided less gain, on average, than the participants' own hearing aids. Consequently, one might expect a difference in speech recognition performance, although one was not observed. This apparent failure to achieve better speech recognition with greater high-frequency gain is most likely attributable to the differences in volume control adjustments with the participants' own linear hearing aids during CST testing, in contrast to the adaptive function of the WDRC instruments. Another possible explanation is that both sets of instruments achieved audibility, although one provided greater gain. The comparisons of the insertion gain curves for the 50 and 80 dB SPL input levels were less similar because of the differences in amplification circuits. The real-ear gain curves for the two groups of subjects, LIN (n = 21) and WDRC (n = 19), are shown separately in Figure 6 with their NAL-R targets. Because the two groups were somewhat different audiometrically (the WDRC group had 5- to 10-dB poorer thresholds in the low to mid frequencies), the gain requirements differed slightly as well. On average, the real-ear insertion gain for the LIN group was slightly below the NAL-R target for the 50 and 65 dB input levels. This is probably due to the fact that the participants set the volume of their instruments at the time of this measurement, whereas the audiologist typically adjusts it to achieve the target at the time of the
fitting. For the WDRC_{ANLG} instruments, only the 50 dB SPL input level yielded a close match to the NAL-R target, reflecting the fact that compression was active over a wider range for the WDRC circuits than for the input compression limiters. These results suggest that, for moderate input levels, audibility was not likely to be a major contributor to possible differences in hearing aid performance. It must be kept in mind, however, that during the CST testing (as in daily use), participants wearing the LIN_{AGC} instruments were allowed to adjust the volume control of their hearing aids for each test condition, whereas the WDRC_{ANLG} instruments had automatic volume control.

**Laboratory Tests of Speech Recognition**

Data are reported as rationalized arcsine units (rau) (Studebaker, 1985), which may be interpreted as percent-correct scores for the range of CST scores observed in this study. Test conditions were compared statistically through analyses of variance. Significant interactions were probed using Scheffe’s F statistic. All statistical tests were conducted with the overall probability of a Type I error set at $p < .05$.

Although the main effect for CST test condition (across hearing aid conditions) was always significant in the various analyses, this finding was of limited interest and will not be discussed.

Figure 7 summarizes the results for each of the three experimental conditions of the BZ5 compared with the first two control conditions, that is, UA performance and performance of NH persons. Consider first the comparison with UA. Because the BZ5_{DR} and BZ5_{DR+NR} programs

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1 In general, the 50 dB, +10 S/N CST condition yielded scores that were significantly better than the 60 dB, REV and 60 dB, 0 S/N, which were often not significantly different from each other but significantly better than the 75 dB, +2 S/N. Scores on the various CST conditions were a function of the presentation levels and speech-to-babble ratios, which were selected to avoid ceiling and floor effects, as well as to represent conditions encountered in everyday listening.
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Figure 7 Mean BZ5-aided CST scores of the 40 participants with hearing loss compared with their unaided performance and with the performance of 20 persons with normal hearing.

were only evaluated under the moderate and high noise conditions (60 dBA, 0 S/N and 75 dBA, +2 S/N), separate analyses were conducted for these two CST conditions and for the UA and BZ5\textsubscript{OMNI} experimental conditions, where complete data were available for all four CST conditions. Scores for BZ5\textsubscript{OMNI} were significantly higher than UA performance ($F = 67.0$; $p < .0001$), although there was a significant interaction with the CST condition. For the quiet (50 dBA, +10 S/N) and REV (60 dBA, REV) conditions, aided performance with the BZ5\textsubscript{OMNI} was significantly better than UA performance ($F = 67.0$; $p < .0001$), although there was a significant interaction with the CST condition. For the quiet (50 dBA, +10 S/N) and REV (60 dBA, REV) conditions, aided performance with the BZ5\textsubscript{OMNI} was significantly better than UA performance ($F = 50.9$, $p < .0001$). There was no significant difference between BZ5\textsubscript{OMNI} and UA performance; however, performance with the BZ5\textsubscript{DR} and BZ5\textsubscript{DR+NR} configurations was both significantly better than UA performance and performance with the BZ5\textsubscript{OMNI} ($F = 45.4$, $p < .0001$). There was no significant difference between the BZ5\textsubscript{DR} and BZ5\textsubscript{DR+NR} configurations for either noise condition.

Next, consider BZ5-aided performance of the 40 hearing-impaired participants compared with that of the 20 NH subjects. Not unexpectedly, the NH listeners performed significantly better than the hearing-impaired participants across the CST conditions ($F = 54.9$, $p < .0001$). It is noteworthy, however, that mean scores for the BZ5\textsubscript{DR} and BZ5\textsubscript{DR+NR} configurations were only approximately 11 raw poorer than those of the NH listeners on the very difficult high-level noise condition (75 dBA, +2 S/N).

Figure 8 summarizes the CST results for the BZ5 compared to the third control condition, that is, the participants' own hearing aids. Data are presented separately for the 21 participants using LIN\textsubscript{ACC} (top panel) and the 19 individuals using WDRC\textsubscript{ANC} hearing aids prior to the clinical trial.
with BZ5DR and BZ5DR+NR performance both significantly better than BZ5OMNI performance and performance with the linear hearing aids. A similar pattern of results was observed for the participants who were wearing the WDRCANLG instruments at the time of enrolment (bottom panel). There was no significant difference between performance with the BZ5OMNI and the participants’ own hearing aids across the test conditions (F = .86, p = .35). For the moderate and high noise conditions, scores for the BZ5DR and BZ5DR+NR were both significantly better than performance with the BZ5OMNI and the participants’ own analog WDRC instruments (F = 32.8, p < .0001).

**PHAB Field Ratings**

Recall that the PHAB was administered to assess benefit with the participants’ own hearing aids at the time of enrolment and at the end of the 6- to 9-week adjustment and trial periods with the BZ5. Further, PHAB ratings were obtained for overall performance with the BZ5, that is, the PHAB questionnaire was not administered separately for each of the three BZ5 programming configurations. Rather, participants were instructed to rate the performance of the BZ5 on each item on the PHAB for the programming configuration (memory) that worked best in that particular situation. Analyses of variance were applied to the PHAB scale and subscale scores.

Figure 9 shows the mean frequency of success ratings (i.e., 100 minus frequency of problems) for the BZ5 compared with each of the three control conditions (i.e., UA, performance by NH persons, and participants’ own hearing aids). Data are shown for three scales and two subscales of the PHAB. As in our earlier clinical trials using the PHAB (Walden et al, 1998, 1999), the subscales derived from the QT and Reduced Cues (RC) scales did not provide different information from the scale scores. Hence, only the scale scores are shown. Significant differences were observed among the three experimental conditions for which there were repeated measures on the 40 hearing-impaired participants (F = 179.9, p < .001). Mean success ratings (across the scales and subscales) were significantly higher for the BZ5 compared with the participants’ own hearing aids (F = 18.1, p < .0001) and for the participants’ own hearing aids compared with UA (F = 57.8, p < .001). A significant interaction was obtained (F = 41.9, p < .001) that reflected a reversal for the Aversiveness (AV) subscale from the pattern seen on the other PHAB measures. Here, greater success was reported for the UA condition compared with the two aided conditions. Post hoc analyses using the Scheffe F statistic revealed that the success ratings for the BZ5, the participants’ own instruments, and UA were all significantly different from one another on each scale and subscale (F = 3.0 – 30.8, p < .01).

Separate analyses were conducted to compare the PHAB ratings from the NH subjects with those of the hearing-impaired participants with their own instruments, with the BZ5, and UA. Mean success ratings were significantly lower for both the participants’ own instruments and the BZ5 compared with normal performance (F = 68.9, p < .0001; F = 40.8, p < .0001, respectively). In both comparisons, the interaction was significant (F = 3.5, p < .01; F = 3.2, p < .05). Post hoc testing revealed that mean (UA) success reported by the NH subjects on the AV subscale was not significantly different from the aided success report by the hearing-impaired participants both with their own instruments and with the BZ5 (Scheffe’s F = .13, p = .97; Scheffe’s F = .02, p = .99, respectively). In contrast, the difference between the ratings of the NH subjects and the UA ratings of the hearing-impaired participants on the AV subscale was significant (Scheffe’s F = 5.75, p < .001). This pattern of findings for the AV subscale has been noted previously (Walden et al, 1998, 1999) and suggests that persons with long-term hearing impairment may develop unrealistic expectations of the intrinsic aversiveness of loud sounds encountered.
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100
n=21
LINAGC
BZ5
across the three scales and two subscales of the PHAB (F = 10.3, p < .01).

Individual Subject Data

Table 2 summarizes individual CST and PHAB data of the 40 participants. Depicted are the number of participants who exceeded the 95 percent critical difference (CD) values when BZ5 aided scores were compared with UA scores and when BZ5 aided scores were compared with aided scores from the participants' own hearing aids. Data are shown for each of the eight test conditions of the CST and for three scales and two subscales of the PHAB. Differences that exceed the CD may be considered highly reliable. Results are shown separately for the LINAGC and WDRCANLG participant groups. The first column of numbers gives the 95 percent CD values. The next two columns show the number of individuals (percent in parentheses) whose BZ5-aided score was significantly higher than their UA score, first for the LINAGC group and then for the WDRCANLG group. Thus, for example, 17 of the 21 participants in the LINAGC group obtained significantly higher scores on the 50 dBA, +10 S/N condition aided with the BZ5OMNi than UA. The next two columns of numbers give the number of individuals whose unaided score was higher than their BZ5-aided score. Similar data are shown for the comparisons between the BZ5 and the participants' own hearing aids in the last four columns of numbers. For example, 7 of the 21 participants in the LINAGC group scored significantly higher on the 50 dBA, +10 S/N CST condition with the BZ5 compared with their own linear hearing aids.

As expected, these data for individual subjects are consistent with the mean group data already presented. In general, most2 participants obtained significant CST benefit from the BZ5 compared with UA performance, although significant benefit from the BZ5OMNI configuration was limited to only a few subjects for the two noisy listening conditions (60 dBA, 0 S/N and 75 dBA, +2 S/N). Most participants reported significant PHAB benefit from the BZ5 (compared with UA) for all three scales of speech understanding (QT, RC, Background Noise [BN]). Compared with their own hearing aids, only a

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2The Food and Drug Administration's statistical criteria for “few” (0-25%), “some” (26-50%), “many” (51-75%), and “most” (76-100%) are used in this report (Food and Drug Administration, 1994).

Figure 10 Mean BZ5-aided PHAB ratings of the participants with hearing loss compared with their own hearing aids. Data are presented separately for the participants who had worn LINAGC (top panel) and the individuals who had worn WDRCANLG (lower panel) hearing aids prior to the clinical trial.
### Table 2: Summary of Individual CST and PHAB Data in Relation to 95% CD Values, Presented for BZ5 Benefit Scores (Aided-Unaided) and for Difference Scores between BZ5-Aided Performance and Performance with the Participants' Own Hearing Aids

<table>
<thead>
<tr>
<th>Measure</th>
<th>95% CD Value</th>
<th>No. of Ss &gt;95% CD in Favor of BZ5 (%)</th>
<th>No. of Ss &gt;95% CD in Favor of Unaided (%)</th>
<th>No. of Ss &gt;95% CD in Favor of BZ5 (%)</th>
<th>No. of Ss &gt;95% CD in Favor of Own Aids (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CST condition</td>
<td>Linear Group (n=21)</td>
<td>WDRC Group (n=19)</td>
<td>Linear Group (n=21)</td>
<td>WDRC Group (n=19)</td>
<td>Linear Group (n=21)</td>
</tr>
<tr>
<td>50/+10</td>
<td>15.5</td>
<td>17 (81)</td>
<td>18 (95)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60/REV</td>
<td>15.5</td>
<td>16 (76)</td>
<td>19 (100)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60/0 OMNI</td>
<td>15.5</td>
<td>7 (33)</td>
<td>5 (26)</td>
<td>2 (10)</td>
<td>0</td>
</tr>
<tr>
<td>60/0 DIR</td>
<td>15.5</td>
<td>15 (71)</td>
<td>17 (89)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60/0 DIR+NR</td>
<td>15.5</td>
<td>17 (81)</td>
<td>19 (100)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70/+2 OMNI</td>
<td>15.5</td>
<td>2 (10)</td>
<td>2 (11)</td>
<td>6 (29)</td>
<td>1 (5)</td>
</tr>
<tr>
<td>70/+2 DIR</td>
<td>15.5</td>
<td>15 (71)</td>
<td>18 (95)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>70/+2 DIR+NR</td>
<td>15.5</td>
<td>12 (57)</td>
<td>18 (95)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PHAB Scale/Subscale (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quiet</td>
<td>16.1</td>
<td>16 (76)</td>
<td>17 (89)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Reduced Cues</td>
<td>19.8</td>
<td>19 (90)</td>
<td>18 (95)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Background Noise</td>
<td>18</td>
<td>19 (90)</td>
<td>18 (95)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Distortion</td>
<td>28.2</td>
<td>3 (14)</td>
<td>4 (21)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Aversiveness</td>
<td>27.8</td>
<td>1 (5)</td>
<td>0</td>
<td>4 (19)</td>
<td>5 (26)</td>
</tr>
</tbody>
</table>

The results are shown separately for the prior users of linear and WDRC instruments. The first column of numbers shows the 95% CD values. The next two columns show the numbers of individuals (percent in parentheses) whose benefit score exceeded the CD in favor of the BZ5. The subsequent two columns show the same data in favor of the unaided condition. The last set of columns shows the numbers of individuals whose aided difference scores were in favor of the BZ5 and those in favor of their previously fitted hearing aids.

The CST 95% CD values are taken from Cox et al (1988) and are based on the six-talker babble on the standard recording. The appropriateness of applying these values to the 60 dBA, 0 S/N test data (noted by asterisks) is unknown because a two-talker babble was used in these test conditions.

Few participants obtained significantly higher CST benefit scores with the BZ5omni and all were wearing LINAGC instruments. On the other hand, many participants obtained significantly greater benefit with the BZ5dir and BZ5dir+NR programming configurations than with their own hearing aids, and this was true whether the participant wore LINAGC or WDRC-instruments. Few participants reported significantly greater benefit with the BZ5 compared with their own instruments on the PHAB, and all but one of those were using linear hearing aids.

### Field Ratings for the Different BZ5 Configurations

Recall that the hearing-impaired participants provided seven subjective ratings of speech understanding, sound comfort, and sound quality/naturalness separately for the BZ5omni, BZ5dir, and BZ5dir+NR programming configurations using 11-point equal-appearing interval scales. These data were analyzed parametrically using analyses of variance. Figure 11 summarizes the ratings for speech understanding in quiet, at a distance (reverberant environments), and in background noise. Relatively small, statistically nonsignificant, mean differences

![Figure 11](image-url)
Figure 12 Mean 11-point scale ratings of sound comfort for nonspeech and speech in noise for the three programming configurations of the BZ5.

Figure 13 Mean 11-point scale ratings of sound quality and naturalness of nonspeech and speech in noise for the three programming configurations of the BZ5.

were observed among the three programs, across the three ratings of speech understanding (F = .66, p = .52). The interaction, however, was significant (F = 3.86, p < .01), reflecting the reversal in the pattern of findings for the quiet and distance ratings versus the noise ratings. Post hoc analyses revealed that none of the differences among the BZ5 programming configurations achieved statistical significance on any of the three ratings of speech understanding (Scheffe’s F = .84–1.25, p = .50–.29). Figure 12 shows the mean field ratings of sound comfort for the three BZ5 configurations for nonspeech sounds (e.g., warning sounds, traffic noise) and for listening to speech in background noise. Significant differences in mean ratings were observed among the three BZ5 programs across the two measures of comfort (F = 5.7, p < .01), with the BZ5DR+NR being rated as significantly more comfortable than the BZ5OMNI. Figure 13 shows the field ratings of sound quality and naturalness of sound for the three BZ5 configurations for nonspeech sounds in quiet (i.e., sounds of nature, music, people’s voices) and for speech in background noise. No significant differences were observed among the three programming configurations (F = .40, p = .67).

**DISCUSSION**

The purpose of this study was to compare hearing aid performance and benefit provided by a number of commercially available technologies, including multichannel WDRC, digital signal processing, dual-microphone directionality, and NR circuitry. Inevitably, the generalizability of the results is limited by the devices evaluated and by certain compromises that had to be made in the design of the study due to its clinical nature. For the most part, these compromises involved the existence of potentially confounding variables. It is difficult to conduct clinical studies where all other variables are held constant between the experimental and control test conditions while a single independent variable is manipulated. Thus, for example, participants entered this study with a minimum of 1 year of experience using their own hearing aids, whereas their experience with the BZ5 at the time of testing was limited to 6 to 9 weeks. Similarly, the participants within the LINAGC and the WDRC groups were fit with two or three hearing aids that differed slightly, whereas the BZ5 was fit to all participants using a constant fitting algorithm.

Within the limitations imposed by the experimental design of this clinical trial, the following conclusions regarding current hearing aid technology appear to be supported by the results.

First, nonlinear WDRC amplification provides slightly greater benefit than linear amplification with input compression limiting. This issue can be addressed by comparing the results of the two participant groups (LINAGC and WDRCANLG) with their own hearing aids. Because the WDRCANLG group had, on average, slightly greater hearing loss in the low to mid frequencies, they actually obtained lower mean aided performance scores on the CST than the LINAGC group (see Fig. 8). When expressed as benefit scores (aided minus UA), however, the advantage of WDRC over linear amplification with input compression limiting becomes apparent. Figure 14 compares benefit scores that were obtained by the participants with their own hearing aids on the CST (top panel) and the PHAB (bottom panel). Mean benefit was significantly greater for the WDRCANLG group than for the LINAGC.
Figure 14  Mean CST (upper panel) and PHAB (lower panel) benefit scores (aided-unaided) of the participants for their own hearing aids for the LIN\text{ADC} (n = 21) and the WDRC\text{ANLG} (n = 19) groups.

There are at least two related reasons why WDRC amplification might provide superior speech recognition to linear amplification (Dillon, 1996). First, because WDRC provides nonlinear gain, audibility is maintained over a wider range of input levels. This feature acts as an automatic volume control. Thus, as a listener encounters different talkers and/or listening situations that vary in average loudness, the hearing aid adjusts the gain to maintain audibility. Although the value and convenience of such automatic adjustments in volume may be considerable, the importance of such processing is tempered by the fact that the volume control of a linear hearing aid can be adjusted by the user when changes in average input levels are encountered in everyday listening. In this regard, Souza and Turner (1999) demonstrated that a given change in audibility has a comparable effect on speech recognition for WDRC amplification and for linear amplification in listeners with mild-to-moderate sensorineural hearing losses.

Many published laboratory studies comparing WDRC and linear amplification have used a constant volume setting for the linear devices, rather than permitting volume adjustments when input levels have varied across test conditions. For example, in studies comparing GN ReSound WDRC devices with linear amplification, Benson et al (1992) and Moore et al (1992) both observed better speech recognition with WDRC at lower input levels. Similarly, in a more recent study comparing linear amplification with a WDRC instrument, Humes et al (1999) also observed better speech recognition with the WDRC device at lower speech presentation levels. In these studies, it appears likely that the rather substantial performance advantages observed for WDRC are attributable primarily to the greater overall gain provided at low presentation levels.

In addition to providing audibility over a wider range of input levels, WDRC circuits that use fast-acting syllabic compression may also provide improved speech understanding by decreasing the consonant-to-vowel intensity ratio, that is, by providing relatively more gain to softer speech sounds (e.g., “s,” “f”) compared with more intense sounds such as vowels within a syllable (Dillon, 1996)\textsuperscript{3}. Such rapid changes in the amplified speech spectrum resulting from WDRC are potentially of greater significance than the effects of relatively long-term volume adjustments because they depend entirely on the unique signal processing provided by the instrument. Recall that participants in this study were permitted to adjust the volume controls of

\textsuperscript{3}Although a decrease in the consonant-vowel intensity ratio should increase the audibility of low-intensity consonants, syllabic compression distorts the normal loudness relationships between speech sounds. To the extent that such loudness relationships are cues in speech recognition, it could be argued that fast-acting compression should reduce speech understanding. Although beyond the scope of this paper, the reader is referred to Plomp (1988) for an early discussion of this issue.
their linear hearing aids prior to each CST condition. Hence, the differences observed between the WDRC and linear devices are more likely attributable to the fast-acting syllabic compression rather than to overall adjustments in volume resulting from the varying input levels used in different laboratory tests.

In an earlier study within our laboratory comparing a GN ReSound digitally programmable two-channel WDRC device with linear amplification (Walden et al, 1999), participants were also permitted to adjust the volume controls of their linear hearing aids prior to each CST condition. Slight performance advantages for two-channel analog WDRC instruments over conventional linear hearing aids were observed, although differences generally were not statistically significant. Interestingly, performance differences between the two amplification systems were most consistently observed for a relatively high presentation level (70 dB) and rather unfavorable S/N (+2 dB), consistent with the findings of Yund and Buckles (1995) and Valente et al (1997). A similar trend, however, was not observed in the present study.

Second, digital signal processing does not provide significantly better performance than comparable analog signal processing. Although there are slight differences between the implementation of WDRC in the (digital) BZ5 and ReSound's earlier analog WDRC instruments (Models BT2, ED3, IC4)—primarily in the number of programmable frequency bands—the signal processing is comparable. It is apparent in the bottom panel of Figure 8 that the BZ5DRN did not provide performance advantages over the WDRCN. The PHAB results also do not reveal large performance differences between the BZ5 and analog WDRC (see Fig. 10, lower panel), although this comparison is complicated by the fact that participants were instructed to rate their performance on the PHAB based on which of the three programs (memories) would perform best in any particular listening situation.

These findings are consistent with other reports that suggest that digital signal processing, in and of itself, does not provide greater benefit than comparable analog signal processing. For example, Bille et al (1999) reported the results of a study that compared speech recognition scores, overall preference, overall satisfaction, and experiences in a variety of everyday listening situations for a digital hearing aid and a comparable analog hearing aid that were identical in appearance. They observed no significant differences between the two devices among their hearing-impaired participants, all of whom were experienced hearing aid users. Similarly, Ricketts and Dhar (1999) observed similar speech intelligibility in digital and comparable analog directional hearing aids in both anechoic and relatively reverberant environments. Generally, comparable findings were also observed by Valente et al (1998, 1999) in a comparison of a digital hearing instrument and analog hearing aids in laboratory measures of speech recognition. In contrast, among listeners with severe hearing impairments, Ringdahl et al (2000) observed slight performance advantages for both digital WDRC and digital linear AGC O (automatic gain control with output limiting compression) instruments compared with analog hearing aids in word recognition in noise, as well as a variety of field ratings of benefit and sound quality.

Although digital signal processing did not provide a performance advantage over comparable analog signal processing in this study, digital technology allows processing of the signal that is not possible with analog circuits (e.g., Powers et al, 1999). Such processing may result in improved listener comfort that, in turn, can increase user satisfaction, even though large improvements in speech recognition do not occur. In any case, it is clear that the future of hearing aid technology is in digital circuitry, particularly in the increased flexibility that is provided by open platform systems. At the present time, it appears that digital technology is progressing faster than our understanding of hearing impairment and signal processing schemes to compensate for the internal distortion that is introduced by cochlear damage. Such signal processing approaches will undoubtedly require the flexibility that is provided by digital systems.

Third, dual-microphone directionality provides significantly better performance under certain listening conditions. The largest hearing aid performance differences observed among the technologies compared in this study were between CST scores for the BZ5OMNI and either the BZ5DR or BZ5DRNR. Mean performance differences were on the order of 20 to 30 percent and highly significant (e.g., see Fig. 7). The superiority of dual-microphone technology over omnidirectional systems in laboratory measures of speech recognition has been observed previously (Valente et al, 1995; Pumford et al, 2000).

Interestingly, the dramatic performance differences observed in the laboratory were not observed as consistently in the field ratings.
Given that different units of measurement were used on the laboratory tests and the various field ratings (e.g., BZ5 and either LIN or LNDR on the BN scale of the PHAB), direct comparison of the laboratory and field measures is questionable. Mueller (1995), however, observed that self-reported benefit is almost always greater than that suggested by objective measures of speech recognition (e.g., Walden et al, 1998, 1999). Large performance differences were not observed between the BZ5 and either the LIN or LNDR on the BN scale of the PHAB (see Fig. 10), where one might have expected a substantial performance advantage for microphone directionality based on the CST results (see Fig. 8). There are relatively few published reports of attempts to document the benefits of microphone directionality using self-assessment questionnaires. In a multisite study of a dual-microphone directional hearing instrument, Valente et al (1999) observed significantly higher benefit scores for the BN scale of the PHAB (site 1) and Abbreviated PHAB (APHAB) (site 2) than the normative data reported by the test developers for linear hearing aids users. Similarly, Preves et al (1999) compared omnidirectional and directional modes in an in-the-ear hearing aid. They observed relatively large performance advantages for the directional mode in laboratory measures of speech recognition in noise. In contrast, when performance of the two modes was directly compared using the APHAB following a 3- to 6-week trial period, relatively small differences were observed.

The 11-point scale field ratings of the different BZ5 memories provide the most direct measure of possible performance advantages for the dual microphones in everyday listening. Although the differences in mean ratings of speech understanding (see Fig. 11) were in the anticipated direction (i.e., BZ5OMNI superior to BZ5DR and BZ5DRNR, in quiet; BZ5DR and BZ5DRNR superior to BZ5OMNI in noise), none achieved statistical significance. In fact, the only significant difference observed for the 11-point rating scale data was between the mean ratings for the BZ5DRNR and BZ5OMNI for listening comfort of speech in background noise. Although less attention has been given to measuring differences between omnidirectional and directional microphone hearing aids in everyday listening than in laboratory settings, Nielsen and Ludvigsen (1978) also noted that field studies tended to show no differences between the two technologies. Similarly, Mueller et al (1983) compared preferences for the omnidirectional and directional modes of a hearing aid in a variety of everyday listening situations after 6 weeks of use. The most common response of their adult hearing-impaired subjects was to express no preference. When a distinct preference was expressed, however, it was most often for the dual-microphone configuration. This was especially true for noisy or otherwise adverse listening situations.

There are several possible explanations for why substantially larger performance advantages for dual-microphone directionality were observed in the laboratory (CST) compared with the ratings obtained in everyday listening situations. First, the laboratory measures probably overestimated the practical benefits that may be obtained from directional microphones under more realistic listening conditions (see Ricketts, 2000, for discussion). The laboratory test procedures created a “best-case” environment for the hypercardioid pattern used in this study. This pattern provided a significantly reduced response to the three speaker positions from which the background noise was presented during the CST, relative to the front speaker position from which the test sentences were presented. Other studies demonstrating a speech recognition advantage of directional microphones over omnidirectional microphones in laboratory environments have often used speech presented at a 0° azimuth and noise from a 180° azimuth, thereby optimizing the separation of the signal and noise in the listening environment (e.g., Valente et al, 1995, 2000; Agnew and Block, 1997). However, other investigators have achieved a more diffuse noise background using multiple loudspeakers in laboratory measures and generally have observed an advantage for directional technology over conventional single-microphone hearing aids (Voss, 1997; Ricketts and Dhar, 1999; Pumford et al, 2000; Ricketts, 2000; Valente et al, 2000).

The low reverberation sound-treated laboratory environment, combined with the relatively short distance between the front loudspeaker and the listener’s head (1.3 m), also provided ideal conditions for the directional configuration. Again, other investigators have demonstrated that directional microphone technology is optimal under anechoic or low-reverberant test conditions and diminishes in its superiority to omnidirectional microphone technology when reverberation times increase (Studebaker et al, 1980; Madison and Hawkins, 1983; Hawkins and Yacullo, 1984; Ricketts and Dhar, 1999; Ricketts, 2000). In a study that considered the effects of both reverberation and
azimuth of the speech versus the noise source, Leeuw and Dreschler (1991) observed better speech recognition performance for directional hearing aids as compared with the omnidirectional hearing aids, both in a low-reverberant room and in a more reverberant space. In the low-reverberant environment, performance improved as the azimuth of the noise source approached 180°. In the more reverberant environment, the superiority of the directional instruments was less than in the low-reverberant room and independent of the azimuth of the noise source.

Nielsen and Ludvigsen (1978) also suggested that the advantage of directional microphones observed in laboratory studies might be severely reduced under conditions of reverberation and diffuse noise such as is frequently encountered in daily life situations. Not all investigators, however, have observed limited benefits of directional microphones in everyday listening. Killion et al (1998) compared intelligibility of speech recorded through omnidirectional and directional hearing aids in a variety of real-world listening situations (e.g., noisy restaurant, crowded street, etc.) and observed performance advantages for the directional microphones that were comparable to those that would be obtained in laboratory settings.

In addition to the possibility that the laboratory measures may have overestimated the practical benefits of microphone directionality, it is possible that the field ratings underestimated those benefits. Perhaps the field measures were not sensitive to the performance differences that existed. Recall that the PHAB was not administered separately for each BZ5 programming configuration. Rather, participants had to anticipate which program (memory) would work best in the listening situation described by each item on the questionnaire and respond accordingly. This rather unorthodox application of the PHAB may have masked differences that would have emerged if the PHAB had been administered in a more conventional manner. Similarly, the reliability and validity of the 11-point scale ratings are unknown. Participants were asked to rate, in a rather abstract sense, the performance of three different programming configurations along seven perceptual dimensions. In contrast to a CST score, which was based on the percentage of 100 key words correctly recognized, only one rating was obtained from each participant for each of the 21 judgments that were required. Further, these ratings tended to be relatively high, raising the possibility of ceiling effects.

In addition to the possibilities that the laboratory measures may have overestimated the advantage of microphone directionality and/or that the field measures may have underestimated this advantage, there are also subject-related issues that may have contributed to the discrepancy between the laboratory and field results. First, it may take longer than 6 to 9 weeks for hearing-impaired patients to learn to use the microphone directionality feature optimally in everyday listening environments. Although earlier research from our laboratory suggests that hearing aid benefit is stable after 6 weeks of use (Surr et al, 1998), other studies suggest that acclimatization effects may continue beyond the first few weeks (e.g., Gatehouse, 1993; Arlinger and Billermark, 1999). Further, it appears likely that optimizing use of directional microphone technology involves more than becoming acclimated to amplified sound. Rather, it requires that the user learns to assess new listening situations to determine whether microphone directionality may provide an advantage and even to modify listening situations when possible to take advantage of directional microphones (e.g., separate speech and noise sources, reduce distance from talker). In this regard, it is important to note that, in an effort to avoid biasing the field ratings, participants in this study were not informed about how the different BZ5 programming configurations worked and in what listening situations they might provide particular benefit. Rather, they were simply told to try the various memories in different listening situations and note which program performed best. Perhaps, with clear instructions regarding how the directional microphones worked and training on structuring noisy listening situations to take advantage of this feature, more dramatic performance advantages for the BZ5\textsubscript{BR} and BZ5\textsubscript{BR+NE} over the BZ5\textsubscript{OMNI} in the field ratings of noisy listening situations would have been observed.

A final factor that might have contributed to the apparent disparity between the directional advantage observed for the laboratory measures and the field ratings is the extent to which the noise conditions, particularly the S/Ns, typically encountered in the daily life of an individual participant were similar to those used in the laboratory test conditions. Recall that the CST presentation levels and S/Ns were selected to yield mid-range scores in the steepest part of the performance-intensity functions. For a listener to obtain noticeably improved performance with directional microphones in

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daily living, it is necessary that the S/Ns routinely encountered yield listening conditions that are neither too easy nor too difficult. If the S/Ns are highly favorable, speech understanding may be asymptotic regardless of the microphone configuration, and the improved S/N provided by the directional microphones will result in little or no improvement in speech recognition. Similarly, if the listening situations routinely encountered are characterized by highly unfavorable S/Ns, the slight improvement in S/N provided by the directional microphones under such circumstances may be of little consequence to the listener's ability to understand the speech message (HG Mueller, personal communication, 2000).

Notwithstanding each of the possible explanations above, the results of this study appear to reflect frequent clinical experience, that is, patients fit with hearing aids equipped with directional microphones often do not report advantages over an omnidirectional microphone in everyday listening situations that are consistent with the large performance advantages frequently observed in the audiometric test booth. Yet, it is clear from controlled clinical/laboratory measures that directional microphone technology offers the potential for very significant improvement in speech understanding in noisy listening situations. Additional work is necessary to determine the extent and circumstances under which the relatively large performance advantages of directional microphones observed in laboratory settings may translate into actual performance advantages in everyday listening.

Fourth, the NR circuit provided little additional benefit over the dual-microphone configuration in speech understanding. In general, small performance differences were observed between the BZ5_{DR} and BZ5_{DR+NR} programming configurations. When performance differences were observed, they typically favored the BZ5_{DR+NR} programming configuration. Recall that the overall output from the BZ5 can be reduced by as much as 7.5 dB when the NR circuit is activated. The effect of this reduced output should be to improve listening comfort in noisy listening situations, as was observed in this study (see Fig. 12). Because the adaptive filtering that is provided by the NR circuit does not change the S/N within listening bands (i.e., critical bands), there is little reason to expect that speech understanding would improve dramatically when the NR circuit is activated (Fabry and Walden, 1990). On the other hand, because the NR circuit results in some attenuation of the amplified signal, audibility could be reduced, thereby potentially reducing speech recognition. In fact, no significant differences in either objective (i.e., CST) laboratory measures or subjective field ratings of speech understanding were observed between the BZ5_{DR} and BZ5_{DR+NR} programming configurations. Again, the small performance differences that were observed generally favored the dual microphones in combination with the NR circuit when background noise was present (see Figs. 7, 8, and 11). Valente et al (1995) and Voss (1997) also observed nonsignificant effects on speech recognition of a “party” algorithm, also based on selective attenuation in different frequency regions, in a dual-microphone hearing aid. Similarly, Ricketts and Dhar (1999) observed little differences between speech recognition performance in a hearing aid set in an omnidirectional mode when a NR algorithm was activated versus when it was not active.

**SUMMARY**

The results of this study suggest that multichannel WDRC amplification can be expected to provide slightly better performance than linear amplification with input compression limiting for typical hearing-impaired adults with moderate-to-severe sensorineural hearing losses. Moreover, WDRC need not be implemented digitally to realize this performance advantage. In this regard, it should be noted that there are other potential benefits to digital hearing aids that were not specifically evaluated in this study. For example, feedback cancellation algorithms can be implemented digitally that are impossible through analog circuitry. For some patients, this can be a compelling reason to recommend a digital hearing aid. Although the immediate benefits of digital technology may be limited at the present time, it is likely that an increasing percentage of hearing aid fittings will be digital as new signal processing algorithms are introduced that are efficacious and only possible through digital technology.

One of the most interesting findings of this study was the disparity between the benefit of microphone directionality observed under controlled laboratory conditions and the participants' impressions of the benefit of directionality in everyday living. Although the reason for this discrepancy is not completely clear, the potential for improved speech understanding in everyday listening is undisputable. It is unlikely that
the potential benefits of directional microphone technology will be realized if it is not used appropriately by the patient. Consequently, patients must be counseled extensively to ensure that they understand how directional microphones work, under what circumstances they will work best, and how to structure noisy listening situations to take advantage of their potential benefit. Finally, NR circuits that are based on adaptive filtering may improve listener comfort under some circumstances but should not be expected to provide noticeable changes in speech recognition.

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