A Comparison of the Aided Performance and Benefit Provided by a Linear and a Two-Channel Wide Dynamic Range Compression Hearing Aid

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The aided performance and benefit achieved with linear and two-channel wide dynamic range compression (WDRC) in-the-canal (ITC) hearing aids were established in 55 individuals. Study participants had been wearing either linear or adaptive-frequency-response (Bass Increase at Low Levels, BILL) ITC hearing aids for approximately one year before participation in this study. Outcome measures included aided performance and objective benefit in quiet and noise at a variety of speech levels (50, 60, and 75 dB SPL), at various levels of babble background (quiet, signal-to-babble ratios of +5 and +10 dB), and for various types of test materials (monosyllabic words and sentences in connected speech). Several subjective measures of aided performance (sound-quality judgments and magnitude estimates of listening effort) and relative benefit (improvement in listening effort and the Hearing Aid Performance Inventory, HAPI) were also obtained. Finally, self-report measures of hearing-aid use were also obtained using daily logs. Participants completed all outcome measures for the linear ITC hearing aids first, following 2 months of usage, and then repeated all outcome measures for the WDRC instruments after a subsequent 2-month period of use.

In general, although both types of hearing aids demonstrated significant benefit, the results indicated that the WDRC instruments were superior to the linear devices for many of the outcome measures. This tended to be the case most frequently when low speech levels were used. Many of the performance differences between devices most likely can be ascribed to differences in gain, and prescriptive approaches (DSL[i/o] vs. NAL-R), for the fixed volume control testing performed in this study.

KEY WORDS: hearing aids, amplification, speech recognition, sound quality, outcome measures

Previous studies have found multiple-channel WDRC hearing aids to provide superior performance to that available from conventional linear hearing aids (Laurence, Moore, & Glasberg, 1983; Moore, 1987; Moore, Johnson, Clark, & Pluvinage, 1992; Yund & Buckles, 1995a, 1995b), although the magnitude of these differences and sample size often have been small. Further, performance comparisons have been made using a limited set of outcome measures. In addition, most comparisons have
been between the performance levels obtained immediately following the fitting of the hearing aids to the patient with no time allowed to adapt to the amplification system. Some studies have shown significant improvements in performance with hearing aids after 1 to 3 months of use, although not all studies report such acclimatization effects (Turner, Humes, Bentler, & Cox, 1996).

An earlier clinical field study (Humes, Christensen, Bess, & Hedley-Williams, 1997), conducted at the same universities participating in the current study, investigated the benefits provided by well-fit linear amplification and an experimental BILL-processing circuit. Both circuits, housed within the same hearing aid (referred to as the C3 hearing aid), provided significant benefit for speech understanding in noise when assessed with two different sets of speech materials (NU-6 and CST), at two speech levels (60 and 75 dB SPL), in two types of background noise (babble and cafeteria noise), and at two signal-to-noise ratios (+5 and +10 dB). Significant benefit was also observed for both the linear and BILL circuits when benefit was evaluated subjectively. Aided performance and benefit, however, were equivalent for both circuits. Magnitude estimates of listening effort were also equivalent for both circuits. Finally, paired-comparison testing indicated no clear preference for one circuit over the other, and this was also evident in the circuit selected for use at the completion of the study.

Having established a baseline for the expected performance of linear and BILL-processing circuits in a large sample (N = 110) of new hearing-aid wearers, the present study sought to measure the performance of a subset of these same participants on many of these same measures of hearing-aid performance and benefit following use of two-channel wide-dynamic-range-compression hearing aids (referred to as D2). Performance with the D2 circuit was compared to that achieved with linear amplification following equivalent 2-month adjustment periods. In addition, because two different sets of hearing aids were used, rather than two different settings of the same hearing aids, paired-comparison testing used in the previous study was replaced by sound-quality judgments obtained with both hearing-aid circuits.

The purpose of this clinical study was to evaluate the binaural performance and benefit of the D2 circuit and compare it to the binaural performance and benefit of a linear circuit. The hearing aids were housed in an in-the-canal (ITC) assembly and were evaluated using objective measures of performance and benefit that are based on speech-recognition scores obtained in quiet and in noise, as well as subjective ratings of benefit, sound quality, and listening effort.

Method

Participants

A participant was eligible for entry into the study if she/he (a) was at least 18 years of age or older and had participated in the prior C3 study; (b) had a flat or gently sloping sensorineural hearing loss (slope 0–15 dB/octave from 250 to 4000 Hz, no inter-octave change of greater than 20 dB); (c) had a hearing loss that was symmetrical (within 10 dB at octave and half-octave frequencies from 250 to 4000 Hz); (d) had thresholds ranging between 25 and 85 dB HL (ANSI, 1996) at any half-octave frequency from 250 to 4000 Hz; (e) had thresholds that were within 10 dB of those established in the C3 study; (f) had received medical clearance by a physician to use hearing aids binaurally; (g) had read, understood, and signed the informed consent form; (h) had normal tympanometry; (i) had an external auditory canal with a size and shape that was consistent with an appropriately sized ITC device; (j) had no cognitive, medical, or language-based conditions that may have limited his/her ability to complete all test procedures; and (k) was not actively participating in any other on-going clinical trials.

Fifty-five individuals who met the above inclusion criteria participated in the study. Using the hearing-loss categories of the prior study by Humes et al. (1997), which were based on better-ear, four-frequency (500, 1000, 2000, and 4000 Hz) pure-tone averages, 23 participants had mild hearing loss (25 dB HL < PTA < 41 dB HL), 25 had moderate hearing loss (40 dB HL < PTA < 61 dB HL), and 7 had severe hearing loss (60 dB HL < PTA < 86 dB HL). Few participants in this study had severe hearing loss because of the requirement in the earlier study that all participants be new hearing aid users. Mean right- and left-ear air-conduction thresholds for each of these subgroups of participants are shown in Figure 1.

Participants were not paid for taking part in this study. However, all participants who completed the study were provided with the D2 hearing aids at no charge.

Hearing Aid

All participants were fit with two binaural sets of ITC-style hearing aids manufactured by Dahlberg, Inc.; one pair of instruments had been fit during the earlier C3 study and the other pair was fit during this study. One participant ultimately was fit with low-profile ITE-style D2 hearing aids because of persistent feedback problems with the ITC configuration. The shells of all hearing aids were unvented during the study period. All hearing aids were tested electroacoustically in accordance with ANSI S3.22-1987 before the start of the trial.
The characteristics of the linear C3 circuit and the fitting rationale have been described in detail previously (Humes et al., 1997). To review briefly, the C3 hearing aids included an experimental BILL circuit that reduced the amount of gain in the low frequencies as the input intensity increased. A manually adjustable potentiometer, accessible only to the audiologist, allowed the BILL circuit to be deactivated. When the circuit was deactivated, the device acted as a linear amplifier. For this study, the BILL circuit was deactivated in all C3 hearing aids so that they would perform as linear devices. This particular linear circuit, however, makes use of a patented Class AB output stage which, according to the manufacturer, incorporates low-distortion peak clipping and has reduced low-frequency circuit noise and low current drain.

The gain, frequency response, and maximum output of each C3 hearing aid were individually selected by the manufacturer to conform with the audiometric characteristics of each test ear. The gain and frequency response were selected to meet the targets prescribed by the revised National Acoustics Laboratory (NAL-R) fitting procedure (Byrne & Dillon, 1986) when set for the linear mode of operation. The desired frequency response was confirmed via probe-tube measurement techniques at hearing-aid delivery. Consistent with the recommendations of Mueller (1992), the real-ear insertion gain of the hearing aid was within 10 dB of the prescribed target at all octave frequencies below 4000 Hz and within 15 dB at 4000 Hz.

The D2 hearing aids incorporated a two-channel WDRC chip. This chip allowed clinician adjustment of the crossover frequency that represents the boundary between the low-frequency and high-frequency channels of the D2, the compression threshold or threshold knee-point (tk) for the wide-band detector (i.e., tk is not channel specific, but applies to both channels), and the compression ratio for each channel (lcr, hcr). Sample electroacoustic frequency responses and input-output functions measured in accordance with ANSI S3.22-1987 are shown in Figure 2. A family of frequency responses is shown for a range of input levels from 60 to 90 dB SPL in 10-dB steps in each panel—with the top panel showing measurements for the highest output circuit (112/45), and the bottom panel providing results for the lowest output circuit (103/43). Compression ratios in each channel are the same in both panels (lcr = hcr = 4:1), as is the crossover frequency separating the two channels (cf = 900 Hz). The compression threshold or knee-point, however, differs in the two panels, with tk = 65 in the top panel and tk = 40 in the lower panel. For each of the compression parameters that could be adjusted by the clinician (cf, tk, lcr, hcr), there was a potentiometer available on the hearing aid. Crossover frequency could vary between 0.9 and 3.9 kHz, compression threshold between 40 and 65 dB SPL, and compression...
Figure 2. Frequency responses and input-output functions (the inset in each panel) for the highest (top panel) and lowest (bottom panel) output versions of the WDRC D2 instruments. Frequency responses in each panel are provided for swept pure-tone inputs ranging from 60 to 90 dB SPL in 10-dB steps. In both panels, the low-frequency and high-frequency compression ratios were set to the maximum possible value (LCR = HCR = 4:1), and the crossover frequency (cf) representing the spectral boundary between the two channels was set to 900 Hz. The compression threshold or knee-point (tk) was set to the highest possible value (tk = 65 dB) in the top panel and the lowest possible value (tk = 40 dB) in the bottom panel. The input-output functions in the insets in each panel were obtained for a 2-kHz pure tone.
ratio (both lcr and hcr) between 1:1 and 4:1. Thus, Figure 2 depicts the maximum compression ratio in each channel and the full range of compression thresholds available. The D2 instruments also had a variable release time for the compression circuit (dual detectors, one fast-acting and the other slow-acting) and made use of a Class D amplifier/receiver.

The gain, frequency response, compression characteristics, and maximum output of the hearing aids were selected individually based on the audiometric characteristics of each test ear. The Desired Sensation Level, DSL [i/o] Version 4.0, procedure was used to generate gain, compression ratios, and maximum output targets (Cornelisse, Seewald, & Jamieson, 1995; Seewald, 1995). The gain targets were specified as real-ear aided responses in ear-canal sound pressure levels for swept pure-tone inputs of 55, 70, and 85 dB SPL and verified in the ear canals of the hearing-aid wearers. DSL[i/o] targets were generated from thresholds and loudness discomfort levels (LDLs) measured in each participant using ER-3A insert earphones. DSL[i/o] targets were calculated and displayed for 55-, 70-, and 85-dB SPL swept pure-tone inputs using software within the Audioscan real-ear system (software version 2.6), and the Audioscan system was used to confirm targets for the 70-dB input signal in all participants. Consistent with the matching criteria used for the linear C3 circuit, the real-ear aided response of the hearing aid for each input level was within 10 dB of the targets at all octave frequencies below 4000 Hz and within 15 dB at 4000 Hz. Following adjustments to the hearing aid to match target gain for the 70-dB input, aided responses were measured for 55- and 85-dB-SPL inputs to verify that the 55-dB aided response was above threshold and the 85-dB aided response was below LDL. The maximum output of the device was selected to be within 10 dB of the SSPL target maximum at octave frequencies from 500 through 4000 Hz.

In Figure 3 the insertion-gain targets for a 70-dB SPL input signal generated by DSL[i/o] for the WDRC D2 hearing aids are compared with those generated by NAL-R for the linear C3 hearing aids. The measured insertion-gain responses for each hearing aid are compared as well. Insertion-gain targets and measurements were generated for Figure 3 by subtracting the real-ear unaided responses from the real-ear aided responses. Results are shown separately for each hearing-loss group, with mild hearing losses in the top panel, moderate hearing losses in the middle panel, and severe hearing losses in the bottom panel. Several observations can be made from these data. First, the two prescriptive procedures, DSL[i/o] and NAL-R, do not prescribe the same frequency responses for moderate level inputs. Although both approaches agree closely in the amount of gain targeted for middle frequencies (750–2000 Hz), the DSL[i/o] approach prescribes considerably more insertion gain than NAL-R both at lower (250, 500 Hz) and higher (3000, 4000, 6000 Hz) frequencies. These differences have been noted previously and are not unexpected (Humes & Halling, 1994). Second, good matches between measured and prescribed insertion gain were achieved for both hearing aids, except in the higher frequencies. Reasonable matches to NAL-R were observed through 4000 Hz for all three participant groups. For the DSL[i/o] procedure, however, good matches were observed only out to a somewhat lower frequency (3000 Hz). Third, for both prescriptive approaches, observed gain at the higher frequencies was considerably lower than that prescribed, with the greatest disparities observed for the DSL[i/o] targets. Nonetheless, the relative differences between the frequency responses prescribed by the two approaches were maintained in the measured frequency responses. That is, the D2 instruments fit with the DSL[i/o] procedure had considerably greater gain in the lower and higher frequencies than the C3 instruments fit with the NAL-R approach.

**Session Schedule**

Participants completed a total of four sessions in this study. The first session, referred to as the "pre-study visit," was conducted to re-establish hearing thresholds since prior participation in the Humes et al. (1997) study about one year earlier. Hearing aids were also evaluated in the test box to assure that they met ANSI S3.22-1987 specifications and, if not, repaired as needed. During this pre-study visit, moreover, all C3 circuits were set to the linear operating mode. This was necessary because, at the conclusion of the prior study of the C3 circuit, participants could opt for a final hearing-aid setting of linear or varying degrees of BILL processing. In addition, instruments could also be vented, if desired by the wearer, at the conclusion of the prior study. During the pre-study visit, the vents were plugged by the clinician to return them to their state in the prior study and to the same state in which the D2 instruments were evaluated in this study. Finally, diaries were distributed to the participants in which they were requested to log their daily hours of C3 instrument usage.

Next was the recruitment visit. During this visit, unaidered and baseline information was obtained from the participants. Earmold impressions were taken as well, and the D2 hearing aids were ordered. To this session was typically 2 to 4 weeks after the pre-study visit.

Two months after the pre-study visit, the participant returned for the dispensing visit, during which aided performance and benefit measures were obtained with the linear C3 instruments and hearing-aid use diaries were collected. Next, the C3 instruments were collected by the clinician; then the D2 instruments were
Figure 3. Mean prescribed (squares) and measured (circles) real-ear insertion gain for the subgroups with mild (top panel), moderate (middle panel), and severe (bottom panel) hearing loss. Filled symbols provide target (NAL-R) and observed insertion gain for the linear C3 device, and unfilled symbols indicate target (DSL/i/o) and observed insertion gain for the WDRC D2 device. Vertical bars above and below the circles represent ±1 standard error about the mean measured gain and, if not visible, were smaller than the size of the symbol.
delivered and adjusted to match the target. Instruction in the use and care of the D2 instruments was provided, and new hearing-aid usage diaries were distributed.

Following 2 months of adjustment to the D2 hearing aids, the participants returned for the final evaluation visit. During this visit, aided performance and benefit measures were obtained with the nonlinear D2 instruments, and hearing-aid usage diaries were collected. Participants were given the choice of wearing either the D2 or C3 hearing aids at the study's conclusion and their preference was recorded. (Both sets of hearing aids, however, were returned to the participant for their use as desired.)

No evaluation of hearing aid benefit took place until after a minimum 2-month adjustment period with either circuit. This adjustment period is consistent with some recent evidence on the possible maturation of hearing aid benefit (Cox & Alexander, 1992; Gatehouse, 1992, 1993) and should allow for plateau performance. It may take several weeks after being fit with a new hearing aid for some wearers to make maximal use of the new amplified auditory information.

During the adjustment period, no changes in the response or casing of the hearing aid were allowed, except when the participant reported physical or loudness discomfort or device malfunction. In typical clinical practice, the audiologist may make fine-tuning adjustments to the client's hearing aid during the first several weeks. These adjustments are typically due to sound-quality preferences on the part of the client. However, these adjustments are not predictable and will vary from client to client. The NAL-R and DSL (i/o) fitting rationales are well developed and generally accepted by audiologists. Therefore, in an attempt to provide consistent responses from participant to participant, variations from the prescribed hearing aid responses were not made.

**Outcome Measures**

Speech levels vary across a broad range in typical communicative environments (Peatsons, Bennett, & Fidel, 1977). In this study, testing was performed at two different speech levels in noise, 60 and 75 dB SPL, which represent normal and raised speech levels (Peatsons et al., 1977) and at two different speech levels in quiet, 50 and 60 dB SPL, which represent soft and conversational levels. Higher speech levels were used in the noise background because it is commonly the case that speech levels increase as the level of the background noise increases (Peatsons et al., 1977). Further, the amount of amplification in the D2 hearing aid varies inversely with the overall input level. By testing at several speech levels, we were able to assess C3 and D2 circuit performance aspects across a range of typical input levels.

Two speech-recognition tests (NU-6, Tillman & Carhart, 1966; Connected Speech Test, CST; Cox, Alexander, Gilmore, & Pusakulich, 1988) were presented in quiet at speech levels of 50 and 60 dB SPL. The NU-6 and CST materials were also presented in noise at speech levels of 60 and 75 dB SPL using multitalker babble and signal-to-noise ratios of +5 and +10 dB. The NU-6 test used in this study was recorded by a female talker (Wilson, Zizz, Shanks, & Caussey, 1990). These measures allowed the examination of aided performance and benefit in a wide range of frequently encountered listening conditions.

All participants completed the 64-item Hearing Aid Performance Inventory (HAPI; Walden, Demorest, & Hepler, 1984) as a subjective measure of benefit. A variety of listening situations are described, and the hearing-aid wearer is asked to indicate how helpful the hearing aid is in each of these situations. A 5-point rating scale is used, with lower numbers indicating greater benefit or help provided by the hearing aid (e.g., “1” corresponds to “very helpful,” and “5” corresponds to “hinders performance”). Although the HAPI consists of four subscales, only composite HAPI scores based on all 64 items were calculated in this study.

In another subjective measure of aided performance, the listener rated the difficulty of listening to speech in babble background and in quiet. The listener heard a 10-sentence encyclopedia-style passage from the CST. Four passages were presented at 60 and 75 dB SPL in babble at +5 and +10 dB signal-to-noise ratios and at 50 and 60 dB SPL in quiet (24 total passages). After each passage, the listener rated “ease of listening” on a 0–100 scale (higher scores representing easier listening or less listening effort required). In each listening condition, the ratings from the last three passages were averaged, and the first was discarded as practice.

Judgments of sound quality (Gabrielsson, Schenkman, & Hagerman, 1988) were also obtained at the dispensing and evaluation visits for aided listening conditions (both C3 and D2). For these subjective performance measurements, the participant was placed in the sound field and presented with segments from passages in the Speech Intelligibility Rating test (Cox & McDaniel, 1989) at 60 and 75 dB SPL in babble at +5 and +10 dB signal-to-noise ratios and in quiet at levels of 50 and 60 dB SPL. The participant heard a 10-s passage and rated the sound quality on the first of the eight quality dimensions listed on the response form. Ten-second passages were repeatedly presented a total of eight times per listening condition, one passage for each quality dimension. The response forms, identical to those described by Gabrielsson et al. (1988), were linear scales ranging from 0 to 10, with adjectives placed above every odd-numbered value along the continuum. Participants simply stated a value between
0.0 and 10.0 after listening to each passage. Oral responses making use of fractions or decimals were permitted. Before collecting data for the actual listening conditions, eight practice passages, each 10 s in length, were presented for random samples of the listening conditions included in the study.

All speech and noise levels specified in dB SPL were measured in sound field at the position of the listener's head using the method of substitution. Speech and noise stimuli were presented from a loudspeaker at 0° azimuth located at a distance of 1 m from the listener's head. Recorded NU-6 materials came from the Department of Veterans Affairs' "Speech Recognition and Identification Materials, Disc 1.1," and the recorded CST and SIR materials were from a CD distributed by the University of Memphis's Hearing Aid Research Laboratory entitled "Speech Intelligibility Tests." The babble used in this study was the multitalker noise available from Auditec, Inc. of St. Louis, Missouri (tape #446).

Before obtaining outcome measures during each session, a passage from the CST was randomly selected for presentation at 65 dB SPL, and the participant independently adjusted the volume control of each hearing aid to a comfortable setting. The 65-dB-SPL presentation level was used for this task because it represented a conversational level and was near the middle of the range of speech levels used in this study. Once set, no further adjustments in the volume control were permitted until the outcome measures were completed. All aided and unaided speech-recognition testing was conducted binaurally.

**Results**

Multiple measures of aided speech-recognition performance were obtained in this study. Figure 4 shows the mean percent-correct performance on the Connected Speech Test (CST) for each of the six listening conditions. Vertical bars represent mean scores for unaided listening (white bars) and the two aided conditions: D2 (black bars) and C3 (striped bars). Measures of benefit were calculated by subtracting unaided performance from aided performance. These measures were subjected to statistical analysis. Following conversion of percent-correct scores to arcsine values (Kirk, 1968) and the calculation of benefit scores, a two-factor (aid, listening condition) repeated-measures analysis of variance was performed on the benefit scores. This analysis indicated that significant benefit was provided by the hearing aids [F(1, 54) = 27.01, p < .05], but that it was not affected by which hearing aid was worn [F(1, 54) = 0.68, p > .05]. The listening condition, however, had a significant effect on the measured benefit [F(5, 270) = 25.84, p < .05], but this interacted with the hearing aid used [F(5, 270) = 5.15, p < .05]. Consequently, multiple paired-sample t tests were compared, one for each of the six listening conditions, to examine the differences in benefit obtained between the linear C3 and the WDRC D2 hearing aids. When adjusted for multiple comparisons (Kirk, 1968), the only significant difference [t(54) = -3.93, p < .01] between hearing aids to emerge was that observed for the 50-dB, quiet listening condition (as noted by the asterisk above the first group of vertical bars in Figure 4). Higher aided speech-recognition scores and significantly higher objective benefit were observed for the D2 hearing aid than for the C3 hearing aid in the 50-dB quiet condition.

Figure 5 shows unaided and aided speech-recognition scores similar to the previous figure, but for the NU-6 monosyllabic word lists. Once again, following arcsine transformation of the percent-correct scores, objective benefit was calculated by subtracting unaided scores from aided scores in each listening condition. A two-factor repeated-measures analysis of variance revealed that significant objective benefit was provided [F(1, 54) = 111.48, p < .05]. Significant effects of both hearing aid [F(1, 54) = 54.18, p < .05] and listening condition [F(5, 270) = 61.72, p < .05] were observed, but these two factors also demonstrated a significant interaction [F(5, 270) = 8.87, p < .05]. Paired-sample t tests, adjusted for multiple comparisons, revealed significant differences (p < .05) between the objective benefit obtained with the C3 and D2 hearing aids for all but one listening condition [t(54) = -2.71, p > .05], as indicated by the asterisks in Figure 5. Benefit measured with the NU-6 lists was significantly better for the WDRC D2 hearing aid compared to the linear C3 hearing aid for every condition except the highest presentation and noise level (75 dB with a +5 dB SNR).

Thus far, the focus has been on the presentation and analysis of group data. Individual data were analyzed to determine the percentages of participants who demonstrated significant objective benefit with each device. Significant differences in unaided and aided scores for individual participants were based on 95% confidence intervals following conversion of percent-correct scores to rationalized arcsine units (RAUs; Studebaker, 1985). RAU-based 95% confidence intervals were ±15.5 RAUs for the CST (Cox et al., 1988) and 18.1 RAUs for the NU-6 materials (Studebaker, 1985). Table 1 shows the percentage of participants showing significant objective benefit for the WDRC D2 instrument and the linear C3 device. Percentages based on NU-6 scores are provided in the top portion of the table, and those derived from CST-based measures of objective benefit are located in the bottom portion of the table.

Several observations can be made from the percentages of significant demonstrations of objective benefit...
in Table 1. In general, regardless of test material or hearing aid, a higher percentage of participants demonstrated benefit in quiet conditions than in noise. The percentage of participants demonstrating significant benefit in noise tended to be highest for the D2 hearing aids and the NU-6 materials. Similarly, the percentage of participants demonstrating significant benefit in noise was higher at 60 dB SPL than at 75 dB SPL, across both test materials and devices.

Turning now to subjective measures of benefit, the mean HAPI score following use of the linear C3 instruments was 1.94 (SD = 0.51), whereas that for the D2 instruments was 1.84 (SD = 0.57). These mean HAPI scores indicate that the participants, on average, found both instruments to be “helpful.” A paired-samples $t$ test revealed that the difference in HAPI scores between instruments was not significant [$t(54) = 1.38$, $p > .05$].

Regarding HAPI scores for individual participants, the percentages of participants who found the linear C3 or WDRC D2 circuits to be either “helpful” or “very helpful,” based on the total HAPI score, appear in Table 2. Percentages in Table 2 are broken down by hearing-loss group. When totaled across all hearing-loss groups, the percentage of participants who found each hearing aid to be helpful or very helpful is remarkably similar. About 85% of the participants found each circuit to be either helpful (63%) or very helpful (22–23%). However, the percentages of participants indicating that each hearing aid provided help varied for each circuit as a function of hearing loss severity. Notice, for example, that 99% of those

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**Figure 4.** Means and standard errors for the percent-correct scores obtained with the Connected Speech Test (CST) unaided (white bars) and with each hearing aid instrument—the linear C3 (striped bars) and the WDRC D2 (black bars)—for each of the six listening conditions included in this study. Each value along the abscissa is labeled with a pair of numbers separated by a comma. The left number of each pair indicates the presentation level of the speech stimulus in dB SPL (50, 60, or 75 dB), and the right number of each pair indicates the level of the background babble (Q = quiet, +10 or +5 dB signal-to-noise ratio). The asterisks indicate significant ($p < .05$) differences between devices.
Figure 5. Means and standard errors for the percent-correct scores obtained with the Northwestern University Auditory Test No. 6 (NU-6) unaided (white bars) and with each hearing aid instrument—the linear C3 (striped bars) and the WDRC D2 (black bars)—for each of the six listening conditions included in this study. Each value along the abscissa is labeled with a pair of numbers separated by a comma. The left number of each pair indicates the presentation level of the speech stimulus in dB SPL (50, 60, or 75 dB) and the right number of each pair indicates the level of the background babble (Q = quiet, +10 or +5 dB signal-to-noise ratio). The asterisks indicate significant ($p < .05$) differences between devices.

Table 1. Percentage of participants showing significant benefit (aided score minus unaided score) on NU-6 and CST tests for each of the six listening conditions (SBR = signal-to-babble ratio).

<table>
<thead>
<tr>
<th>Conditions</th>
<th>50 dB Quiet</th>
<th>60 dB Quiet</th>
<th>60 dB +10 dB SBR</th>
<th>60 dB +5 dB SBR</th>
<th>75 dB SBR</th>
<th>75 dB +10 dB SBR</th>
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<td>NU-6</td>
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<tr>
<td>D2 vs. unaided</td>
<td>87</td>
<td>89</td>
<td>29</td>
<td>60</td>
<td>20</td>
<td>31</td>
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<td>51</td>
<td>44</td>
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<td>27</td>
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<tr>
<td>C3 vs. unaided</td>
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<td>45</td>
<td>44</td>
<td>40</td>
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<td>25</td>
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with mild hearing loss found the linear C3 circuit to be either helpful or very helpful, whereas only 43% of those with severe hearing loss indicated this to be the case. On the other hand, 79% of those with mild hearing loss found the D2 circuit to be helpful or very helpful, whereas 100% of those with severe hearing loss found this to be true.
Figure 6 provides the mean data for another measure of subjective performance and benefit: magnitude estimation of listening effort (MLE). Recall that in this task, the listener is asked to assign a number from 0 to 100 to a speech passage presented in one of six listening conditions in which the number assigned reflects the

Table 2. Percentage of participants who found the C3 or D2 hearing aids to be helpful (HAPI score from 1.51 to 2.50) or very helpful (HAPI score less than or equal to 1.50).

<table>
<thead>
<tr>
<th>HL group</th>
<th>C3</th>
<th>C3</th>
<th>C3</th>
<th>C3</th>
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<td>Mild (N = 23)</td>
<td>82</td>
<td>17</td>
<td>99</td>
<td>57</td>
<td>22</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Moderate (N = 25)</td>
<td>56</td>
<td>28</td>
<td>84</td>
<td>65</td>
<td>26</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>Severe (N = 7)</td>
<td>29</td>
<td>14</td>
<td>43</td>
<td>83</td>
<td>17</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>All participants</td>
<td>63</td>
<td>22</td>
<td>85</td>
<td>63</td>
<td>23</td>
<td>86</td>
<td></td>
</tr>
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</table>
"ease of listening." Assigning a value of "100" means that it was very easy to listen to and understand the speech passage, whereas "0" indicates that this was very difficult. Mean listening-effort ratings are provided in Figure 6 for unaided and aided listening, for both the WDRC D2 and the linear C3 hearing aids. A two-factor, repeated-measures analysis of variance, performed on the subjective benefit for the 55 participants, revealed that (a) significant benefit was provided $[F(1, 54) = 18.84, p < .05]$; (b) there were significant differences in benefit between the two hearing aids $[F(1, 54) = 6.02, p < .05]$; (c) there were significant differences in benefit across listening conditions $[F(5, 270) = 40.96, p < .05]$; and (d) the differences between hearing aids interacted significantly with the listening conditions $[F(5, 270) = 14.64, p < .05]$. As a result, the between-aid differences in subjective benefit were examined separately for each of the six listening conditions using paired-sample $t$ tests. When adjustments were made for multiple comparisons, only two significant between-aid differences in benefit emerged ($t(54) = –6.22$ and $–2.90$, $p < .05$, in the 50 dB Q and 60 dB Q listening conditions, respectively) as indicated by the asterisks above the vertical bars in Figure 6. These significant differences indicate that there was greater improvement in the ease of listening, relative to the unaided listening effort, with the WDRC D2 hearing aid than with the linear C3 hearing aid in the two low-intensity, quiet listening conditions.

Recall that the listeners were asked to judge the quality of running speech along eight dimensions and in six different listening conditions involving various presentation levels and signal-to-noise ratios, using the procedures of Gabrielson et al. (1988). For each of the quality dimensions, a geometric mean rating across all six listening conditions was calculated. The mean of these geometric means is shown for each of the eight quality dimensions and for each hearing aid (C3 vs. D2) in Figure 7. The asterisks above each pair of vertical bars indicate the significant ($p < .05$) differences between the quality ratings for the linear C3 and the WDRC D2 instruments based on Wilcoxon Signed-Ranks tests. In all cases of significant differences, the average quality rating is higher for the WDRC D2 than for the linear C3 instrument. With the exception of the loudness dimension, higher numbers reflect better quality, although it is only for the "total quality" dimension that a rating of "10" is considered to be "ideal" (Gabrielson et al., 1988). Overall, the sound quality when wearing the WDRC D2 hearing aids was judged to be superior to that obtained while using the linear C3 devices.

The mean values for another subjective outcome measure, self-reported hearing-aid usage, were 7.19 h (SD = 2.65) and 7.85 h (SD = 3.15) for the C3 and D2 instruments, respectively. A paired-samples $t$ test revealed this to be a significant difference ($t(54) = –2.17$, $p < .05$). On average, the participants wore the WDRC D2 hearing aids more hours per day than they did the linear C3 instruments.

A final evaluation of differences between the two hearing-aid circuits was obtained at study completion by asking each participant which hearing aids, the WDRC D2 or the linear C3 hearing aids, they would wear now that the study was completed and both sets of ITC hearing aids were in their possession. Forty-two (76%) of the 55 participants indicated that they would be wearing the WDRC D2 hearing aids. Chi-square testing indicated that this was a significant preference for the D2 instruments ($\chi^2(1) = 15.3$, $p < .05$). When asked on the questionnaire to indicate a reason for their final preference, 83.6% indicated their decision was based on "performance" differences, 12.7% indicated "other" reasons, and 3.6% said "cosmetics" was the reason for their choice (even though both were configured as ITC instruments).

**Discussion**

It is noteworthy that the group data revealed significant objective benefit from both the linear C3 and WDRC D2 hearing aids on the objective NU-6 and CST measures of speech recognition, as well as considerable subjective benefit based on ratings from the HAPI. Ease of listening was also found to be significantly enhanced with both hearing aids as opposed to unaided listening. Additionally, group differences in performance and benefit, measured either objectively or subjectively, were observed frequently between the C3 and D2 hearing aids. When such differences emerged, they were always in favor of the WDRC D2 instruments over the linear C3 devices. Frequently, however, the observed differences between devices were confined to the lower speech presentation levels.

There are several obvious explanations for the observed performance and benefit differences between the C3 and D2 hearing aids. First, WDRC hearing aids have nonlinear gain characteristics such that more gain is provided for lower input sound levels than for high input levels. Given that the gain of both devices was set to a comfortable loudness level for a 65-dB-SPL input signal, it is likely that the C3 hearing aids provided less gain than the D2 instruments at the lower presentation levels of 50 and 60 dB SPL. Thus, participants would be expected to receive more of the speech signal with the D2 devices than with the C3 devices at these lower levels and to perform better in quiet as a result. Had participants been able to adjust the volume controls of both devices in each listening condition, it is possible that these performance and benefit differences between the two devices would have been reduced or negated.
Aside from differences in gain characteristics as a function of input level between the two instruments, the prescriptive procedures used to fit each device also varied. The DSL[i/o] procedure was used with the D2 hearing aid and the NAL-R method with the C3 device. As noted previously (Figure 3), for the same moderate input level (70 dB) depicted in that figure, the DSL[i/o] procedure prescribes more gain in the high and low frequencies than the NAL-R procedure. Thus, it is impossible to determine whether the observed differences in performance between the D2 and C3 circuits are due to the electronics in the devices or to the procedures used to fit them to the wearers. Perhaps if the C3 device were to have a frequency response similar to that prescribed by the DSL[i/o] procedure for moderate inputs, it would yield results comparable to those observed here for the D2 device.

The primary purpose of this study was to compare the performance and benefit provided by two different hearing-aid prototypes being considered for production by the manufacturer, when fit with the procedures intended for each type of technology and likely to be used by dispensers of these instruments. In this regard, the WDRC D2 hearing aids fit using the DSL[i/o] procedures appear to be superior to the linear C3 instruments fit with the NAL-R method.

In addition to differences in input-output functions and fitting procedures, the D2 and C3 devices differed in at least one other key characteristic. The C3 device made use of a Class AB amplifier with peak clipping to limit maximum output, whereas the D2 instrument made use of a Class D amplifier and output-limiting compression. Class D devices are known to be quieter and have less distortion than either Class A or Class B amplifiers.
(at least as typically configured in most hearing aids). Thus, the observed differences in sound quality between the two devices could be attributable, at least in part, to electronic differences between the devices independent of the differences in input-output functions.

Whatever the underlying reasons, the performance and benefit differences in favor of the D2 circuit were validated at the study’s conclusion through the participants’ selection of the hearing aid they planned to wear after the study. Consistent with the observed differences in performance and benefit, the vast majority of participants (76%) indicated that they planned to use the D2 instruments after study completion. This preference, however, could be due to the order bias of the study introduced by the fact that all participants wore the D2 instruments for 2 months after using the linear C3 devices. Participants may have simply preferred the instrument worn most recently (the D2). The order bias resulted from some practical constraints confronted by the manufacturer and is unlikely to have had an impact on the measures of speech recognition, sound quality, listening effort, and subjective benefit (HAPI) obtained in the study. Nonetheless, it is interesting that 76% of the participants preferred a new circuit, the D2, over the one that they had been wearing for at least the past 14 months, the C3 worn with either the linear or BILL setting.

It is of interest to determine if the final preference for the D2 or C3 circuit could be predicted from some of the dependent measures of this study. To examine this, a discriminant analysis was performed on the data. The groups, defined on the basis of their preference for either the C3 or D2 hearing aids, could be identified with 89% accuracy by considering the differences in their scores for the C3 and D2 hearing aids for each of the following measures: (a) objective benefit measured with the CST at 60 dB SPL and a +10 dB signal-to-noise ratio; (b) softness quality ratings; (c) loudness quality ratings; and (d) objective benefit measured with the NU-6 materials at 50 dB SPL in quiet. Other variables considered in the discriminant analysis included the age and hearing loss of the participant, the aided and unaided scores on the NU-6 and CST measures, all measures of objective benefit, and sound quality. All the variables under consideration are such that they could be obtained from the hearing-aid wearer without requiring actual extended periods of usage. This is not the case for the HAPI or the subjective usage outcome measures, and they were not included in the discriminant analysis. To the extent that acclimatization will not affect the four outcome measures identified in the discriminant analysis, it would be possible to predict, with almost 90% accuracy, the circuit selected or preferred by the wearer by obtaining two measures of objective benefit and two sound-quality measures with the C3 and D2 circuits, each fit with their respective prescriptive approaches. These measurements could be performed by the audiologist using electroacoustically flexible and easily coupled behind-the-ear D2 and C3 hearing aids before ordering the preferred circuit in the preferred physical packaging (ITE, ITC, CIC, etc.). Compared to a strategy of making only D2 devices available, which would err in this study 24% of the time, an approach based on discriminant functions would reduce the errors in circuit selection to 11%. Further investigation of such a comparative approach to circuit selection is required to ensure that assumptions underlying such an approach (Walden, Schwartz, Williams, Holum-Hardegen, & Crowley, 1983) would be valid in this application.

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