Monaural/Binaural Preferences: Effect of Hearing Aid Circuit on Speech Intelligibility and Sound Quality

Sharmala V. Naidoo*
David B. Hawkins†

Abstract

This investigation compared monaural and binaural hearing aid preferences of 15 adults with mild-to-moderately-severe bilaterally symmetrical sensorineural hearing losses. Subjects listened to connected discourse in quiet and background noise at 70 and 80 dB SPL with K-Amp, linear Class D, linear output limiting compression (OLC), Manhattan II, and linear asymmetrical peak clipping circuits (APC). In Experiment 1, subjects made judgments of sound quality and speech intelligibility in a modified paired-comparison paradigm during which they compared the monaural and binaural fittings of each circuit. In Experiment 2, subjects engaged in subjective ratings on a scale of 0 to 10. Subjects benefitted from improved sound quality and speech intelligibility in high-noise conditions when fit with binaural K-Amp, linear Class D, linear OLC, and Manhattan II circuits. Monaural listening was preferred with the APC circuit. Results indicate that improved sound quality and speech intelligibility may be obtained with binaural fittings of circuits that include high fidelity, low distortion, or increased headroom.

Key Words: Binaural hearing aids, K-Amp, Manhattan II, output compression, peak clipping

Abbreviations: APC = asymmetrical peak clipping, Man II = Manhattan II, OLC = output limiting compression

Numerous studies have examined the subjective and objective advantages of binaural hearing aids (Bergman, 1957; Carhart, 1958; Dirks and Carhart, 1962; Byrne and Dermody, 1975; Brooks and Bulmer, 1981; Byrne, 1981; Cox and Bisset, 1984; Dermody and Byrne, 1975a; Hawkins and Yacullo, 1984; Mueller, 1986). A principle finding has been the documented improvement of word recognition scores in noise under laboratory conditions (Belzille and Markle, 1959; Zelnick, 1970; Dermody and Byrne, 1975b; Causey and Bender, 1980; Sebkova and Bamford, 1981). This is a particularly important finding when one considers that hearing-impaired persons with sensorineural hearing losses experience great difficulty understanding speech in noisy environments, and that the use of binaural hearing aids may provide a method of improving speech recognition under these conditions.

Despite these objective findings, subjective reports of binaural hearing aid use in routine noisy situations (Dirks and Carhart, 1962; Byrne, 1981; Erdman and Sedge, 1981, 1986; Brooks, 1984; Schreurs and Olsen, 1985) have been incongruent with the results from the laboratory studies. Byrne (1980) reported evidence of a monaural hearing aid preference in noisy situations. He surveyed 99 adults who were monaural hearing aid users for 2 to 20 years. The subjects were provided with binaural amplification 6 to 8 weeks before administration of questionnaires. They compared binaural and monaural hearing aids in 11 specific situations. Results revealed that only 41 percent preferred binaural hearing aids when listening to speech in high-noise environments. Forty-three percent indicated a monaural preference and 16 percent indicated no difference. In a similar
study, Schreurs and Olsen (1985) found that 55 percent of hearing-impaired persons who were surveyed preferred binaural hearing aids in quiet environments and 55 percent preferred a monaural hearing aid in noisy situations. Comparable findings have been reported by other researchers (Dirks and Carhart, 1962; Byrne and Upfold, 1986; Erdman and Sedge, 1986).

In summary, while laboratory studies have revealed improvements in word recognition scores in noise with binaural hearing aids, subjective reports from hearing aid users have indicated preferences for a monaural hearing aid when listening to conversation under noisy situations, clearly denoting a disparity between laboratory and field observations.

There are three noticeable differences between the laboratory and field studies that may account for the discrepancy: (1) the type of amplification used under research conditions is generally very controlled, (2) the listening environment in the laboratory often does not simulate real-life acoustics, and, finally, (3) objective word recognition tasks in the laboratory may not be representative of listening tasks in the field.

Custom-built instruments have typically been used in binaural laboratory research. In some cases within an experiment, researchers use the same (often high-fidelity) hearing aid across subjects (Jerger et al, 1961; Nabelek and Robinson, 1982). On leaving the laboratory environment, hearing-impaired persons wear personal amplification that may be substantially different from the amplification device used in the research study. Subjective comparisons of monaural and binaural hearing aids are then based on personal amplification.

A related issue in the field studies is the era in which the studies were conducted. Most of the studies reporting a monaural preference in noisy environments were completed in the early 1980s (Byrne, 1980; Schreurs and Olsen, 1985) when the main option available was traditional linear hearing aid circuitry. Linear amplifiers can produce high distortion when saturated depending on the type of output limiting used. In traditional linear hearing aids, the maximum output may be controlled by either peak clipping or output limiting compression (OLC). The use of peak clipping results in the generation of distortion products at high sound inputs, which consequently affects sound quality and clarity (Agnew, 1988; Cox and Taylor, 1993; Hawkins and Naidoo, 1993). However, peak clipping is still the most popular mode of output limitation (Hawkins and Naidoo, 1993).

Potential solutions to the problem of increased distortion are the use of OLC, linear Class D receivers (which provide more headroom and less chance of saturation), and nonlinear hearing aids. Nonlinear circuitry may incorporate automatic signal processing (ASP) with level-dependent frequency responses, such as “bass increases at low levels” (BILL) and “treble increases at low levels” (TILL). The Manhattan II is an example of the BILL approach. It was developed with the belief that the low-frequency gain of the circuit should be attenuated in the presence of high input levels to reduce upward spread of masking. The K-Amp is an example of the TILL approach. It represents a high-fidelity circuit that addresses the problem of performance in environments of intense acoustic input. The circuit provides amplification for low-level sounds and almost no gain at high inputs, consequently increasing user comfort at high acoustic inputs.

Prior to the introduction of such circuits, linear hearing aids were routinely dispensed and extensively used in research through the early 1980s. As a result, generalizations from earlier investigations, including research on monaural/binaural preferences, may be invalid for current hearing devices.

A second difference between the research and field studies involves the listening environment in which comparisons are made. Under laboratory conditions, speech input levels are often representative of normal conversational levels (Jerger et al, 1961; Hawkins and Yacullo, 1984; Balfour and Hawkins, 1992). In addition, more favorable signal-to-noise (S/N) ratios, atypical of everyday listening situations, are frequently used in laboratory studies. Under research conditions, many studies have adopted presentation levels ranging from 65 to 70 dB (Jerger et al, 1961; Hawkins and Yacullo, 1984; Balfour and Hawkins, 1992). During laboratory tests, it can therefore be expected that the hearing aids were operating in their linear range below saturation, with minimal hearing aid distortion. In contrast, outside the laboratory, personal hearing aids may have been saturating in moderate-to-high input conditions that are characteristic of everyday noise situations. In such a situation, linear hearing aids that are limited by peak clipping would generate considerable distortion and could reduce speech intelligibility (Crain and Van Tasell, 1993; Hawkins and Naidoo, 1993). As a result, the type of personal amplification and the higher levels of input to the hearing aid outside the laboratory are impor-
tant variables to consider when evaluating monaural versus binaural hearing aid preferences.

With the availability of newer circuitry with level-dependent frequency response and lower hearing aid distortion, it is of interest to determine whether binaural preferences depend on the type of hearing aid circuitry that is used. However, an important aspect of this research would be the type of response task required of subjects. Speech discrimination in binaural hearing aid research has typically been assessed by word recognition scores. These objective measures of speech intelligibility, however, may not be representative of the subjective methods of assessment used by hearing-impaired persons in everyday life. Subjective measures of monaural/binaural hearing-aid performance have used questionnaires (Byrne, 1980, 1981; Schreurs and Olsen, 1985) to assess general responses in different listening environments, such as the percentage of persons using one or two hearing aids in different environments, or a retrospective rating on a 10-point scale (Brooks and Bulmer, 1981) without analyses of the criteria used during monaural and binaural choices. Gabrielson and Sjogren (1974, 1975a, b, 1977) and Gabrielson et al (1980) have provided an alternative approach to the measurement of hearing aid sound quality, developing a sensitive measure of subjective responses in different listening conditions.

The purpose of the present investigation was to determine whether monaural and binaural preferences are affected by the type of hearing aid circuitry. The hypothesis was that lower distortion circuits may produce a greater binaural preference, better speech understanding, and improved sound quality in noise. Specifically, a person listening with traditional hearing aids having higher distortion would prefer one hearing instrument in noisy environments, while a person listening with more current instruments having lower distortion would prefer binaural amplification. We evaluated the hypothesis in two experiments. A modified paired-comparison paradigm was used in Experiment 1 and a 10-point rating scale was administered in Experiment 2.

METHODS

Subjects

Fifteen hearing-impaired adults with a mean age of 65 years (range of 23–85 years) with mild-to-moderate sensorineural hearing losses participated in the study. The hearing losses were bilaterally symmetrical with interaural asymmetries in average pure-tone thresholds for 500 to 4000 Hz less than 15 dB. Thirteen of the 15 subjects were current hearing aid users (12 binaurally and 1 monaurally aided). The hearing aids of nine of the subjects were limited by peak clipping. The hearing aids of the remaining subjects used OLC. The two subjects who were unaided were interested in amplification but had not yet obtained hearing aids.

Hearing Aid Circuits

Five pairs of custom-built amplifier circuits were used in the study. These included the K-Amp, linear Class D, Manhattan II, linear with asymmetrical peak clipping (APC), and linear with OLC. Each pair of the multi-amplifier units was housed in a small box and coupled via left and right modules to behind-the-ear (BTE) hearing aid cases via cords that connected to the hearing aid microphone and receiver. The BTEs were coupled to the subject's ears via custom clear soft half-shell earmolds with pressure release vents.

Each unit had a switch that enabled selection of either monaural or binaural settings. The K-Amp and Class D circuits were housed in the same unit with a switch that enabled alternation between the circuits. The units included volume control wheels (VCW) and low-frequency tone controls for each module. This allowed each unit to be adjusted to match National Acoustic Laboratories (NAL) prescribed gain target values (Byrne and Dillon, 1986) for each subject within 3 to 4 dB. In addition, SSPL90 controls were present in the APC and OLC boxes. The left and right modules in each circuit were closely matched in gain, frequency response, and output levels. The 2 cm³ coupler frequency response for the linear circuits were matched within 3 to 4 dB.

Stimulus

The stimulus was a recording of a speech passage from a National Geographic magazine read by a practiced adult male with a General American dialect. The noise consisted of a 12-talker babble from the Revised Speech Perception in Noise Test (Bilger et al, 1984). Two presentation levels of speech were used: 70 dB SPL and 80 dB SPL, chosen to represent normal and slightly raised speech. For the speech-in-
noise condition, the S/N ratio at the 70 dB SPL presentation level was +5 dB and was +1 dB at 80 dB SPL. These two S/N ratios were chosen to represent a typical noisy situation and a poor situation when voices are raised, respectively.

Procedures

The tone controls on each hearing aid circuit were adjusted for each subject to best match the revised NAL's 2-cc coupler recommended frequency response slope from 500 to 2000 Hz. A composite speech weighted noise of 70 dB SPL was used to obtain frequency response slopes for the linear Class D, APC, and OLC hearing aids. Due to the level-dependent frequency response and nonlinear characteristics of the K-Amp and Manhattan II circuits, frequency response slopes for these circuits were adjusted using 50 dB SPL speech-weighted noise inputs.

Data were collected in two 2-hour sessions over a 3-week period, in a listening booth (2.68m x 1.94m x 1.31 m) with an average reverberation time of 0.19 seconds for the frequencies 500, 1000, 2000, and 4000 Hz. The speech stimulus was routed through an audiometer, amplified, and delivered to a Realistic Minimus loudspeaker located at 1.2 m from the subjects at a 0° azimuth. The 12-talker babble was recorded on two tracks of a Yamaha MT-100 four-track tape recorder. Each uncorrelated noise track was routed through an audiometer, amplifier and delivered through two Realistic Minimus loudspeakers located 1.5 m from the subject at 135° and 225° azimuths. The combined level of the noise at the position of the subject was set at 65 dB SPL for the 70 dB SPL speech-in-noise condition (S/N of +5) and 79 dB SPL for the 80 dB SPL speech-in-noise condition (S/N of +1). The levels of speech and noise were calibrated daily with a Larson-Davis 800B sound level meter.

Subjects were fit with each circuit with the frequency response preset to best match 2-cc coupler target "user gain" NAL values. The monaurally aided ear was randomly selected unless the subject indicated a preference when listening with one ear. The preferred VCW settings for speech in quiet and in noise were determined for each circuit while listening monaurally and binaurally (subject instructions in Appendix A) at the two presentation levels (70 and 80 dB SPL).

Maximum output was set below previously obtained uncomfortable loudness levels. These settings were validated for the OLC and APC circuits while subjects listened to the 80-dB presentation level. Two procedures were used to gather data on the dimensions of sound quality and speech intelligibility: (1) modified paired-comparison judgments and (2) ratings on a 10-point scale.

Modified Paired-Comparison Task

In the modified paired-comparison task, the experimenter alternated between monaural and binaural hearing aids, and the subject judged the sound quality and speech intelligibility by comparing one and two hearing aids. The pace at which the experimenter switched between monaural and binaural listening arrangements was determined by the subject. Subjects then selected between the two listening arrangements and indicated the strength of their preference through a method described by Dillon (1984) and used in similar studies (Balfour and Hawkins, 1992; Hawkins and Naidoo, 1993). Subjects were provided with specific instructions and scales for the sound quality and speech intelligibility modified paired-comparison judgments (Appendix B).

Ratings on a Scale of 0 to 10

In the second procedure, subjects rated the sound quality and speech intelligibility with each of the circuits on a 10-point scale while listening with one and two hearing aids. Instructions and rating scales provided to subjects for sound quality and speech intelligibility judgments appear in Appendix C.

Experiment 1. In the first session, prior to data collection, subjects practiced modified paired-comparison decisions and strength of preference judgments of sound quality and speech intelligibility for a speech passage in quiet and in noise and at two presentation levels (70 and 80 dB SPL).

During data collection, the experimenter alternated between monaural and binaural hearing aids via the switch mounted on each unit. The earmold was physically removed during monaural listening to represent a realistic monaural environment. In the binaural condition, the earmold was replaced in the ear and the unit switched to a binaural function. This was continued until the subject made a written choice between one or two hearing aids. The VCWs were also altered back and forth to previously obtained monaural and binaural preferred
settings. Conditions were randomized and repeated, resulting in a total of 80 listening trials in groups of five periods with 16 conditions per period (8 sound quality and 8 speech intelligibility).

**Experiment 2.** During the second session, all electroacoustic and VCW settings were analogous to those used in session one. Subjects listened to the identical conditions as in session one but with either one or two hearing aids. In other words, the experimenter did not alternate between one and two hearing aids in each condition. Written ratings of the sound quality and speech intelligibility of the speech passage were made on a scale of 0 to 10.

Subjects practiced ratings for each condition prior to data collection. There were two repetitions per condition, resulting in 160 trials across five sessions. Each period was divided into 16 monaural and binaural conditions, 8 of which were sound quality and 8 were speech intelligibility ratings. All conditions were randomized.

**Statistical Analysis**

Since the data generated by these experiments are ordinal in nature, it would be appropriate to analyze them by nonparametric statistical methods. However, Levitt et al (1995) have recently demonstrated that, so long as ratings are not too widely spread, one can apply parametric statistical techniques to such data without serious consequence. Accordingly, we have elected to analyze the present data by standard parametric analyses of variance. Statistical significance was evaluated at the 5 percent confidence level.

**RESULTS**

**Experiment 1**

The first experiment used a modified paired-comparison paradigm to obtain subject preferences for monaural and binaural hearing aids on subjective dimensions of sound quality and speech intelligibility. Subject ratings were scored according to the recommendations of Dillon (1984) and were identical to those used by Hawkins and Naidoo (1993). A "slightly better" response was assigned a value of 1, "moderately better" was 3, and "much better" was 5. Preferences for binaural hearing aids were designated positive values, and preferences for a monaural hearing aid were assigned negative values. The results for sound quality and speech intelligibility were analyzed separately. An analysis of variance for repeated measures for both sound quality and speech intelligibility indicated a binaural preference when averaged across circuits, presentation level, and background noise (F = 13.40, p < .01 for quality; F = 10.82, p < .01 for intelligibility).

**Sound Quality Preference Data**

**Response Category Trends.** Table 1 is a list of the mean sound quality preference data for the fifteen subjects averaged across the hearing aid circuits, presentation level, and listening background. An analysis of mean sound quality preference data for each subject revealed a range of scores from -1.5 to 3.35, when averaged across all circuits, presentation level, and background noise, with 73 percent of subjects indicating binaural preferences. The question of interest in this investigation was whether monaural/binaural preferences varied as a function of circuit type, presentation level, and background noise.

**Effect of Hearing Aid Circuits.** The mean monaural/binaural preferences for sound quality for the five hearing aid circuits averaged across presentation level and speech in quiet and noise are shown in Figure 1. Binaural preferences for the K-Amp were the strongest (2.28), followed by OLC (1.55), and Class D (1.32). It is clearly evident that monaural/binaural preferences were dependent on hearing aid circuit (F = 38.32, p < .01). The mean score for the Manhattan II was 0.59, and a slight monaural preference of -0.69 was obtained for the APC. The mean monaural/binaural preferences on the sound quality dimension for all five hearing aids were statistically different from 0 (p < .01;

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<th>Strength of Preference</th>
<th>Binaural Preferences (%)</th>
<th>Monaural Preferences (%)</th>
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<tr>
<td>1 (slight)</td>
<td>34</td>
<td>14</td>
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<td>3 (moderate)</td>
<td>29</td>
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<td>5 (high)</td>
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Figure 1 Mean modified paired-comparison preference for monaural vs binaural condition on the sound quality task for each of the five hearing aid circuits averaged across presentation level and background noise. Data from Experiment 1.

Table 2 Mean Strengths of the Monaural and Binaural Preferences for Speech Intelligibility in Experiment 1

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<th>Strength of Preference</th>
<th>Binaural Preferences (%)</th>
<th>Monaural Preferences (%)</th>
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<tr>
<td>1 (slight)</td>
<td>42</td>
<td>10</td>
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<td>3 (moderate)</td>
<td>36</td>
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<td>5 (high)</td>
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Effect of Presentation Level and Background Noise. Monaural/binaural preferences were dependent on presentation level (F = 73.52, p < .01). Data revealed a slight-to-moderate binaural preference (1.71) at 70 dB SPL and a very small (0.31) binaural preference at 80 dB SPL. Monaural/binaural preferences for sound quality were the same in quiet and in a background of noise.

Speech Intelligibility Preference Data

Response Category Trends. Table 2 shows the mean preference responses of the 15 subjects averaged across hearing aid circuits, presentation level, and background noise. Eighty-six percent of the subjects revealed binaural preferences. An analysis of mean speech intelligibility preference data for each subject indicated a range of scores from -0.25 to 2.65 when averaged across all circuits, presentation level, and background noise. All subjects revealed similar trends in responses, despite differences in personal amplification systems and length of binaural hearing aid use. We addressed the same overall question with speech intelligibility data as we did with the sound quality data, namely, whether the speech intelligibility monaural/binaural preferences were dependent on type of hearing aid circuit, presentation levels, and/or background noise. The mean response data with the five hearing aid circuits varied as a function of background noise, and responses at the two presentation levels varied as a function of background noise, indicating the presence of interactions in the data.

Effect of Hearing Aid Circuits as a Function of Background Noise. The mean scores for the five hearing aid circuits for speech in quiet and speech in noise are shown in Figure 2. The largest binaural preference (2.47 in quiet and in noise) was obtained with the K-Amp, followed by OLC (1.98 in noise and 2.03 in quiet) and Class D (1.28 in noise and 1.22 in quiet). While there was a binaural preference for the Manhattan II (0.81) in noise, there was no significant
preference (0.42) in quiet. APC revealed a significant (p < .05) binaural preference for speech in quiet (0.55) and a monaural preference in noise (−0.58). These results suggest that when subjects listened to speech in quiet, they experienced improved speech intelligibility with binaural K-Amp, Class D, OLC, and APC amplifiers. They were, however, unable to note any differences in speech intelligibility between monaural and binaural fittings of the Manhattan II circuit. When listening in a background of noise, these subjects indicated improved speech intelligibility when listening with binaural K-Amps, Class D, OLC, and Manhattan II circuits, and with monaural APC.

**Effect of Presentation Level as a Function of Background Noise.** Monaural/binaural preferences for speech in quiet and in background noise varied at the two presentation levels (F = 2.97, p < .05). Binaural preferences were present in quiet and noise for 70 and 80 dB SPL presentation levels, with stronger binaural preferences at 70 dB SPL than at 80 dB SPL (p < .008).

In summary, the results of the first experiment indicate that sound quality was improved with binaural K-Amp, linear Class D, OLC, and Manhattan circuits, and with a monaural APC circuit, irrespective of the presentation level and background noise. Similarly, speech intelligibility was improved with binaural K-Amp, OLC, and Class D circuits at both presentation levels and for speech in quiet and in noise. Results with the Manhattan II circuit revealed no differences in speech intelligibility with one or two Manhattan II circuits when subjects listened to speech in quiet. However, when listening in background noise, speech intelligibility improved with binaural Manhattan II circuits.

Results with the APC amplifier demonstrate that when listening to speech in a background of noise, the subjects preferred speech intelligibility with a monaural APC. However, in the absence of background noise, binaural APC produced slightly better speech intelligibility than the monaural listening situation.

**Experiment 2**

In this experiment, subjects rated sound quality and speech intelligibility on a scale of 0 to 10 while listening with the five hearing aid circuits monaurally and binaurally in quiet and in noise at presentation levels of 70 and 80 dB SPL.

**Sound Quality Results**

Mean ratings of the 15 subjects averaged across circuits, number of hearing aids, presentation level, and background noise ranged from 5.36 to 8.81 (fair to very good sound quality). Subject response trends across conditions were similar.

**Effect of Hearing Aid Circuit and Presentation Level.** Figure 3 shows the mean ratings of sound quality for the five hearing aid circuits as a function of presentation levels. There were minimal (p > .008) differences in ratings for K-Amp, Class D, and OLC across presentation levels, with all ratings at 6.84 or higher. Ratings for the Manhattan II and APC, however, were dependent on the presentation level. At the higher presentation level, ratings for the Manhattan II were significantly lower than K-Amp, Class D, and OLC (p < .008). The effect of presentation level was even more dramatic with the APC circuit (p < .0001), which had a rating of 5.11 (fair sound quality) at 80 dB SPL and a rating of 7.35 (rather good sound quality) at the 70 dB SPL presentation level. At this high presentation level, APC was rated significantly lower (p < .0001) than the K-Amp, OLC, Class D, and Manhattan II. At the lower presentation level, K-Amp was rated significantly higher (p < .001) than OLC but was not significantly different from Class D, Manhattan II, or APC (p > .008).

**Effect of Monaural/Binaural Hearing Aids and Hearing Aid Circuits.** The mean ratings of the five hearing aid circuits as a function of one or two hearing aids are shown in Figure 4. Differences in ratings of sound quality for
monaural and binaural hearing aids depended on the type of hearing aid circuitry ($F = 7.40$, $p < .01$). The interaction between monaural/binaural hearing aids and circuits was primarily due to the APC circuit, which was rated significantly higher ($p < .005$) with one hearing aid. There were no significant differences with one and two hearing aids for the Class D, OLC, and Manhattan II ($p > .01$). Subjects did, however, rate the K-Amp (7.75) significantly higher with two hearing aids ($p < .01$) than with one (7.11), a finding that is consistent with the results in Experiment 1, where there were greater binaural preferences in sound quality with the K-Amp than any other circuit.

When listening with two hearing aids, K-Amp was rated the highest (7.75), followed by Class D (7.07), OLC (7.0), Manhattan II (6.75), and APC (5.68). K-Amp was rated significantly higher than any of the four other circuits ($p < .01$) and APC was rated significantly lower than any of the other circuits ($p < .01$). An interesting finding was that the ratings of sound quality when listening with the five circuits were similar monaurally but different binaurally, indicating that binaural amplification may be a more sensitive means of assessing differences in sound quality.

**Speech Intelligibility Results**

The mean speech intelligibility ratings of the 15 subjects averaged across circuits, number of hearing aids, presentation level, and background noise indicated a range from 5.37 to 9.87 (fair to very clear). All subjects indicated similar trends across the conditions. The question posed was whether subjects' speech intelligibility responses were influenced by monaural/binaural hearing aids, circuitry, presentation level, and background noise.

**Effect of Monaural/Binaural Hearing Aids, Hearing Aid Circuit, and Background Noise.** The mean speech intelligibility ratings with monaural and binaural fittings of the five circuits for speech in quiet and speech in noise are shown in Figure 5. The most expected finding was that all ratings of speech intelligibility dropped in the presence of background noise. Another anticipated outcome was the "clear" to "very clear" rating of speech intelligibility across all binaural circuits for speech in quiet. The effect of noise was more varied. APC was rated the lowest with both one (6.37) and two hearing aids (6.09), with no significant differences between the ratings. An interesting finding was that subjects rated speech intelligibility in background noise ($p < .01$) higher with a monaural Manhattan II (7.06) than with binaural Manhattan II circuits (6.07).

In quiet, speech intelligibility ratings with binaural K-Amp (9.04), Class D (8.51), OLC (8.57), and Manhattan II (8.47) were higher than monaural ratings (8.54, 7.64, 8.34, and 7.95) with the same circuits. However, only ratings with binaural Class D circuits were significantly higher than monaural amplification ($p < .01$).

In background noise, speech intelligibility was rated as rather clear with binaural K-Amp (7.32), OLC (6.92), and Class D (6.61). Ratings

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**Figure 4** Mean ratings of sound quality (Experiment 2) on a scale of 0–10 for monaural and binaural fittings as a function of hearing aid circuits averaged across presentation level and background noise.

**Figure 5** Mean ratings of speech intelligibility (Experiment 2) on a scale of 0–10 for monaural and binaural fittings as a function of hearing aid circuits and background noise averaged across presentation level.
with binaural Manhattan II (6.07) and APC (6.09) were significantly lower (p < .01) than binaural K-Amp, OLC, and Class D. Furthermore, there were no significant differences in speech intelligibility among monaural hearing aids when listening in noise, suggesting that binaural amplification is more sensitive to differences in speech intelligibility in background noise.

In summary, the purpose of the second experiment was to determine whether ratings of sound quality and speech intelligibility for connected discourse varied across monaural and binaural fittings of the five circuits. An expected finding was that speech intelligibility dropped drastically in the presence of background noise for each hearing aid circuit (Martin and Pickett, 1970; Plomp, 1978; Trees and Turner, 1986). However, speech intelligibility was rather clear when listening with either monaural or binaural K-Amps, linear Class D, and OLC circuits. Although similar ratings were observed for monaural Manhattan II, speech intelligibility dropped with binaural fittings of this circuit. An interesting finding was that subjects reported the poorest speech intelligibility with both monaural and binaural APC and the poorest sound quality with binaural APC. Furthermore, the five circuits were almost always ordered in the following manner: K-Amp, Class D, OLC, Manhattan, and APC. From the above results, it appears that the subjects preferred binaural K-Amps, Class D, and OLC at low and high presentation levels, both in quiet and in noise in the modified paired-comparison paradigm, and benefitted from improved sound quality and speech intelligibility as evidenced by measures of ratings in Experiment 2. An unexpected finding was that while subjects’ ratings of the five hearing aid circuits were similar monaurally, significant differences were evident when listening binaurally.

DISCUSSION

The major purpose of the study was to determine the effects of selected hearing aid circuitry on preferences for monaural and binaural amplification. Differences in the method of data collection between the two experiments should be understood before the data are interpreted as a whole. In the first experiment, a modified paired-comparison paradigm was used. Subjects listened with each circuit and made preference judgments of sound quality and speech intelligibility by comparing monaural and binaural circuits. In the second experiment, subjects listened to random presentations of the five circuits monaurally and binaurally and engaged in ratings of sound quality and speech intelligibility. They were not directly comparing monaural and binaural amplification. Instead, they made ratings based on the relative performance of each circuit. There were differences in results between the two experiments, which may have been due to the listening tasks and responses required of the subjects. Paired-comparison tasks, in general (provided they are well executed), have been demonstrated to be more sensitive.

However, the overall results indicate that persons with mild-to-moderately-severe sloping symmetrical sensorineural hearing losses demonstrate improved speech intelligibility and sound quality with selected binaural high-fidelity, low-distortion hearing aid circuits. The strength of preference for binaural K-Amps was consistently higher than for any other circuit. In addition, the K-Amp circuit received the highest ratings on a scale of 0 to 10. Subjects reported improved sound quality and speech intelligibility with the binaural K-Amp circuit, which could be related to the reduction in gain and change in frequency response with increasing input signal level.

The K-Amp was manufactured with the supposition that persons with mild-to-moderate hearing losses are unable to hear low-intensity sounds but function adequately in the presence of high-intensity sounds. In this regard, the K-Amp attempts to amplify low-level sounds so that they are audible, and as the level of the input to the hearing aid increases, the gain is decreased. For typical VCW positions and inputs of 80 dB SPL and higher, the hearing aid becomes "transparent." The advantages are twofold: (1) listeners need not tolerate increased output from the hearing aid with high levels of input and (2) the chance of saturation-induced distortion is minimized. The result is high-fidelity production of intense environmental signals without sacrificing user comfort, coupled with improved sound quality and intelligibility of speech, as evidenced by the present study. Similar findings were reported by Knight (1992). In her investigation, hearing-impaired subjects who subjectively compared K-Amp hearing aids with their personal linear circuits preferred binaural K-Amps more often than those fit monaurally.

Despite the claims of superior performance of the Manhattan II circuit in high-noise envi-
environments (Darland et al, 1993), in the present study, this circuit was almost always ranked fourth. A plausible explanation could be related to the frequency response observed with high-level inputs. At low input levels, the Manhattan II has a broad low-frequency response. As the input level increases, the adaptive filter in the circuit automatically reduces low-frequency gain up to 30 dB, resulting in a large difference in frequency response of the Manhattan II for inputs of 80 dB SPL compared to the remaining four circuits used in the study, in particular when compared to the reduced high-frequency gain provided by the K-Amp circuit. At this high intensity, the gain of the instrument was restricted to 2000 to 5000 Hz. A probable explanation for poorer performance of the Manhattan II could be that the sample of hearing-impaired listeners used in the investigation preferred the enhanced sound quality and improved speech intelligibility with the frequency response of K-Amp, Class D, and OLC than with the high-pass frequency response provided by Manhattan II. Although research has shown that high-frequency amplification provides maximum speech recognition for persons with sloping high-frequency losses, the gain in the high frequencies should be carefully selected (Skinner, 1980; Sullivan et al, 1992).

The third type of circuit used in the present investigation was the linear Class D. The Class D circuitry varies from traditional Class A type linear circuitry. It is a high-fidelity amplifier that is able to produce up to 110 to 115 dB SPL maximum output with minimum distortion. The linear OLC was the fourth circuit used in this research. This circuit is known to produce minimum distortion once saturation is reached.

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**Figure 6** Coherence measurements for A, K-Amp, B, OLC, C, Class D, D, Manhattan II, and E, APC.
Research (Crain and Van Tasell, 1993; Darland et al., 1993; Hawkins and Naidoo, 1993; Hogan et al., 1993; Potts et al., 1993) demonstrates that better sound quality and speech intelligibility are produced by newer nonlinear circuits than those limited by peak clipping circuitry. This correlates with the present finding of monaural preferences with APC at high levels of input, which is known to produce more distortion as saturation increases (Crain and Van Tasell, 1993; Hawkins and Naidoo, 1993).

Many of the recent changes in hearing aid design have addressed the issue of distortion. There has been gradual gravitation toward circuitry that minimizes distortion, a trend that is most noticeable in programmable amplification. The major difference between traditional and programmable hearing aids is that the latter have incorporated low-distortion circuitry. Linear circuits do not routinely use low-distortion circuitry (e.g., compression) as a form of output limiting. A survey of hearing aid manufacturers (Hawkins and Naidoo, 1993) revealed that in 1991, 82 percent of all hearing aids sold in the United States incorporated peak clipping. It is apparent through the results of this study that in intense noise environments, circuitry that produces high-fidelity signals, greater headroom, and less output distortion is preferred binaurally due to improved speech intelligibility and sound quality.

The magnitude of distortion for the five different circuits was determined through the use of coherence measures with inputs of 50 to 90 dB SPL. The results are shown in Figure 6. Minimal distortion was evidenced at all input levels for the K-Amp and OLC circuits. Class D and Manhattan II circuits showed reduced coherence at 80 and 90 dB SPL inputs. The APC circuit showed the poorest coherence functions, especially at higher input levels. The shift in coherence for the Manhattan II circuit at the low frequencies may be due to noise as the output signal level is reduced and not to distortion. These quantitative measures of magnitude-squared coherence distortion correlate well with the subjective measures obtained in the study and provide credence to the effect of distortion on subjective measures of speech intelligibility and sound quality.

In everyday noisy situations, it is possible that hearing aids are frequently in saturation. This means that for persons fit with linear peak clipping hearing aids, there is a greater chance of signals being clipped at moderate and high input levels. Perhaps in these situations of increased distortion, hearing aid users prefer one distorting hearing aid to two, a hypothesis that is supported by this study. The data in this investigation suggest that the use of cleaner, high-fidelity circuits, even at high levels of input and in the presence of noise, lead to binaural preferences.

One of the interesting findings in the second phase of the study was that subjects did not note differences in sound quality and speech intelligibility with monaural fittings of the circuits. They did, however, perceive differences when listening binaurally. This, in effect, provides further support for the advantages of binaural listening. This is an important finding in that many clinical comparisons between new and traditional circuits are typically completed with monaural hearing aids and most often in quiet. In this investigation, differences among circuits were apparent when the subjects listened binaurally, especially in noise. For instance, subjects could not tell differences in sound quality when listening monaurally; however, with binaural amplification, they rated APC far lower than the other four circuits. This should be an expected finding in view of the documented advantage of binaural listening in noise and on psychoacoustic tasks. As an example, improved difference limens for intensity have been demonstrated with binaural compared to monaural presentations (Hawkins and Wightman, 1980; Hall and Fernandes, 1983). Based on these findings, hearing aid comparisons that use monaural fittings may be insensitive or less sensitive to some differences among hearing aids.

There are several limitations to this study, one of which is that subjects were relatively inexperienced listeners. Due to the time constraints imposed during the investigation, subjects made subjective decisions about binaural and monaural preferences in the course of 5 to 6 hours of listening. According to Gatehouse (1992), this is insufficient time to acclimatize to hearing aids. Perhaps long-term use of monaural and binaural hearing aids may result in different preferences from those obtained in this study. Although the type of personal hearing aids (peak clipping and OLC) and length of hearing aid use varied across subjects, there were no apparent effects on the study. An analysis of individual data demonstrated that subjects were fairly similar in their responses during the investigation. Almost all subjects in the present study were binaural users. Further research is needed to determine the effect of previous monaural and binaural hearing aid use on similar questions.
Another limitation may be the type of stimuli and S/N ratios used in this research. All four listening conditions were fixed, with speech levels of 70 and 80 dB SPL and S/N ratios of +5 and +1 dB. Levels of speech and noise encountered in real life may fluctuate considerably (Teder, 1990). Individual lifestyles and listening environments of hearing aid users vary. The clinical implications are that hearing aid evaluations should be based on sound inputs encountered in situations where persons most often use their hearing aids.

Furthermore, the present design did not permit modified paired-comparisons of various binaural circuitry (i.e., binaural K-Amps to binaural OLC, Class D, Manhattan II, or APC). The modified paired-comparison approach is highly sensitive to differences between hearing aids (Hawkins and Naidoo, 1993; Dirks et al, 1995; Levitt et al, 1995) and warrants further research.

In summary, the results of this investigation revealed that the APC circuit provided increased distortion with an input of 80 dB SPL, as confirmed by coherence measures, and that subjects reported improved speech intelligibility and sound quality in high-noise conditions with binaural fittings of “cleaner,” high-fidelity amplifiers. These results have implications for hearing aid fitting. Clients fit with linear amplification, who often complain of difficulties listening in noise, may benefit from binaural circuits that keep the hearing aid out of saturation, or that deliver “cleaner” outputs when the instrument is in saturation. Hearing-impaired persons that are fit with circuits with high distortion have two deficits to deal with: (1) distortions created by an impaired hearing mechanism and (2) additional distortion created by the hearing aid circuitry. As a result, circuits that introduce saturation-induced distortion should be avoided. In addition, our findings indicate that binaural hearing aid comparisons may be more sensitive to subjective dimensions of speech intelligibility and sound quality than monaural hearing aid comparisons.

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REFERENCES


Monaural/Binaural Preferences/Naidoo and Hawkins


APPENDIX A

Instructions for Setting Volume Control Wheel Positions for Monaural and Binaural Conditions

I want to set the hearing aid(s) to a level that is comfortable to you. Try to select a level that you would be able to listen to for a long time. I shall switch between one and two hearing aids. We need to make sure that the two hearing aids are equally loud as one. Remember, two hearing aids should not be louder than one, nor should one hearing aid be softer than two. Indicate to me whether you want me to increase or decrease the volume. When listening with two hearing aids, you should hear the speech located at the center of your head.

APPENDIX B

Instructions for Modified Paired-Comparison Paradigm

Sound Quality

I want you to listen to two hearing aid arrangements, one hearing aid in your ___ ear and hearing aids in both ears. Think of which has a better, more pleasing sound quality. Decide which of the hearing aid arrangements, one or two, sounds more pleasant. You have to decide which you prefer and how strongly. You can select from prefer it just slightly, moderately, or much more. There are no correct or incorrect answers. You can switch from one to two hearing aids as many times as needed before you make a judgment.

The subjects were supplied with the following options to describe their preference:

___ Two hearing aids have much better sound quality than one.
___ Two hearing aids have moderately better sound quality than one.
___ Two hearing aids have slightly better sound quality than one.
___ One hearing aid has slightly better sound quality than two.
___ One hearing aid has moderately better sound quality than two.
___ One hearing aid has much better sound quality than two.

Speech Intelligibility

I want you to listen to one and two hearing aids and decide which has better speech intelligibility. Think of whether you can understand more speech with one or two hearing aids—in other words, which arrangements allow you a clearer understanding of speech. You have to decide which arrangement you prefer and how strongly. You can select from prefer it just slightly, moderately, or much more. There are no correct or incorrect answers. You can switch from one to two hearing aids as many times as needed before you make a judgment.

The subjects were supplied with the following options to describe their preference:

___ Two hearing aids have much better speech intelligibility than one.
___ Two hearing aids have moderately better speech intelligibility than one.
___ Two hearing aids have slightly better speech intelligibility than one.
___ One hearing aid has slightly better speech intelligibility than two.
___ One hearing aid has moderately better speech intelligibility than two.
___ One hearing aid has much better speech intelligibility than two.
### APPENDIX C

**Instructions for Ratings on a Scale of 0 to 10**

**Sound Quality**

You need to decide on the sound quality of the speech. Think of how pleasing the speech sounds. Then rate it on the following scale of 0 to 10, with 10 representing the best possible sound quality and 0 the worst possible sound quality.

<table>
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<th>10%</th>
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<th>30%</th>
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<th>70%</th>
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<th>90%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>worst</td>
<td>very bad</td>
<td>rather bad</td>
<td>fair</td>
<td>rather good</td>
<td>very good</td>
<td>best</td>
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</tbody>
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**Speech Intelligibility**

You need to decide on the intelligibility of the speech. Think of how much of the speech you can understand and how clear the speech is to you. Then rate it on the following scale of 0 to 10, with 10 representing complete (maximum) understanding of the speech and 0 representing no (minimal) understanding of the speech.

<table>
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<tr>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
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<th>70%</th>
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<tbody>
<tr>
<td>minimum</td>
<td>very unclear</td>
<td>rather unclear</td>
<td>fair</td>
<td>rather clear</td>
<td>very clear</td>
<td>maximum</td>
<td></td>
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