Are Two Ears Not Better Than One?

DOI: 10.3766/jaaa.23.3.4

Rachel A. McArdle*†
Mead Killion‡
Monica A. Mennite§
Theresa H. Chisolm*†

Abstract

Background: The decision to fit one or two hearing aids in individuals with binaural hearing loss has been debated for years. Although some 78% of U.S. hearing aid fittings are binaural (Kochkin , 2010), Walden and Walden (2005) presented data showing that 82% (23 of 28 patients) of their sample obtained significantly better speech recognition in noise scores when wearing one hearing aid as opposed to two.

Purpose: To conduct two new experiments to fuel the monaural/binaural debate. The first experiment was a replication of Walden and Walden (2005), whereas the second experiment examined the use of binaural cues to improve speech recognition in noise.

Research Design: A repeated measures experimental design.

Study Sample: Twenty veterans (aged 59–85 yr), with mild to moderately severe binaurally symmetrical hearing loss who wore binaural hearing aids were recruited from the Audiology Department at the Bay Pines VA Healthcare System.

Data Collection and Analysis: Experiment 1 followed the procedures of the Walden and Walden study, where signal-to-noise ratio (SNR) loss was measured using the Quick Speech-in-Noise (QuickSIN) test on participants who were aided with their current hearing aids. Signal and noise were presented in the sound booth at 0° azimuth under five test conditions: (1) right ear aided, (2) left ear aided, (3) both ears aided, (4) right ear aided, left ear plugged, and (5) unaided. The opposite ear in (1) and (2) was left open. In Experiment 2, binaural Knowles Electronics Manikin for Acoustic Research (KEMAR) manikin recordings made in Lou Malnati's pizza restaurant during a busy period provided a typical real-world noise, while prerecorded target sentences were presented through a small loudspeaker located in front of the KEMAR manikin. Subjects listened to the resulting binaural recordings through insert earphones under the following four conditions: (1) binaural, (2) diotic, (3) monaural left, and (4) monaural right.

Results: Results of repeated measures ANOVAs demonstrated that the best speech recognition in noise performance was obtained by most participants with both ears aided in Experiment 1 and in the binaural condition in Experiment 2.

Conclusions: In both experiments, only 20% of our subjects did better in noise with a single ear, roughly similar to the earlier Jerger et al (1993) finding that 8–10% of elderly hearing aid users preferred one hearing aid.

Key Words: Hearing aids, hearing loss, speech recognition

Abbreviations: GLM = General Linear Model; KEMAR = Knowles Electronics Manikin for Acoustic Research; QuickSIN = Quick Speech-in-Noise; REIR = real-ear insertion response; rms = root-mean-square; SNR or S/N = signal-to-noise ratio; VA = Department of Veterans Affairs

*Bay Pines VA Healthcare System, Bay Pines, FL; †University of South Florida, Tampa, FL; ‡Etymotic Research Inc., Elk Grove Village, IL; §Albany ENT, Albany, GA

Rachel A. McArdle, Ph.D., Bay Pines VA HCS, Audiology (126), PO Box 5005, Bay Pines, FL 33744; Phone: 727-398-9395; Fax: 727-319-1209; E-mail: Rachel.mcardle@va.gov

Portions of this paper were presented at the American Auditory Society, March 5–7, 2008, Scottsdale, AZ.

This manuscript is based upon work supported by the Department of Veterans Affairs, Veterans Health Administration, and Office of Research and Development, Rehabilitation Research and Development Service through a Research Career Development award to the first author, and a pre-doctoral fellowship to the third author. The contents of this manuscript do not represent the views of the Department of Veterans Affairs or the United States government.

Research examining the benefits of binaural versus monaural amplification has occurred for over 50 yr. The theory that the outcomes of binaural amplification will be superior to those from monaural amplification, in terms of speech recognition in noise, is based on the known benefits of listening with two ears as compared to one, or the known benefits of binaural listening (e.g., Carhart, 1946; Keys, 1947; Hirsh, 1948; Koenig, 1950).

One of the benefits of binaural listening is the binaural squelch effect, which occurs when the noise and the signal of interest come from two different locations (Kock, 1950; Carhart, 1965). As a result of the noise and the signal coming from different directions, the total waveforms of the signals reaching each ear are dissimilar, resulting in a dichotic listening situation. The dichotic signals are combined centrally, resulting in an effective signal-to-noise ratio (SNR) that is higher than the SNR that would occur when listening through either ear alone (Carhart, 1965).

Dillon (2001) provides an excellent example of how binaural squelch occurs. In his example noise arrives from 0° azimuth, or directly in front of the listener, while a high frequency pure tone "signal" arrives from 90° azimuth, or the right side of the head. Due to the head shadow effect, the intensity of the signal is higher at the right ear than the left ear; while the noise characteristics are the same in both ears. The brainstem appears to act similar to an electronic subtraction circuit that subtracts the waveform at the left ear from the waveform at the right ear. This subtraction results in partial cancellation of the noise and an improvement in SNR of about 2 to 3 dB.

Dillon (2001) points out that a "perfect subtraction" is not possible; imperfect combinations of the waveforms arriving at both ears result in the binaural squelch phenomenon. Carhart (1965) demonstrated that with normal hearing individuals, binaural squelch can result in a 5 to 11% improvement in speech recognition performance over that which occurs when listening with only one ear. Listeners with hearing loss can benefit from the phenomenon of binaural squelch, although the benefits may decrease as hearing loss increases (Durlach et al, 1981).

Another benefit to binaural listening is binaural redundancy, which is the advantage obtained from receiving the same or identical information about the signal and the noise in both ears (diotic listening), which is postulated to result in a suppression of the internal noise within each ear, allowing for improved decision making centrally (Stearns and Lawrence, 1977). Dillon (2001) describes this phenomenon as one in which the brain gets two "looks" at each sound. Research has shown that diotic listening results in an improvement in SNR of 1 to 2 dB (MacKeith and Coles, 1971; Bronkhorst and Plomp, 1988). The binaural redundancy advantage can apply to both listeners with normal hearing and listeners with hearing loss (Day et al, 1988).

Given the benefits of binaural listening for improving SNR, it might be expected that a binaural hearing aid fitting would result in better speech-in-noise recognition performance, when compared to a monaural fitting. Indeed, as reviewed by Ross (1980), there are several early studies that support the assumption that there will be better speech recognition performance with the use of two hearing aids as compared to one (e.g., Markle and Aber, 1958; Belzile and Markle, 1959; Wright and Carhart, 1960; Olsen and Carhart, 1967). On the other hand, there are also early studies that suggest no difference in monaural versus binaural speech recognition in noise performance (Hedgecock and Sheets, 1958; DiCarlo and Brown, 1960; Jerger and Dirks, 1961). In reviewing these studies, Ross postulated that the major factor differentiating those studies showing benefit from those that did not was speaker location and the origin of the speech and noise signals. Although Dirks and Wilson (1969) found no differences in speech recognition performance between monaural and binaural conditions when the speech and noise were both coming from the same speaker located at 0° azimuth, a binaural advantage was observed when speech and noise came from separate speakers (noise was coming from the front speaker [0° azimuth] and the signal coming from the right side of the listener [90° azimuth]).

Two more recent studies that questioned the importance of two hearing aids looked at objective (Henkin et al, 2007) and subjective (Cox et al, 2011) benefits of unilateral versus bilateral amplification. Henkin et al reported better speech-in-noise performance for 71% of their 28 participants using one hearing aid on their "better" ear than using two hearing aids. Similarly, Cox et al reported 46% of their 94 participants preferred to use one hearing aid rather than two hearing aids.

In a recent review of research comparing binaural to monaural amplification, Mencher and Davis (2006) concluded that 90% of adults performed better with two hearing aids (specifically, 10% of adults demonstrate a negative binaural interaction). In addition, Mencher and Davis identified several methodological factors that might account for a lack of finding a significant binaural advantage in laboratory studies, one being that earlier research used either very few subjects or very few test scores, making it difficult to show a statistically significant difference in performance.

Although methodological issues may account for the lack of finding a binaural advantage in many of the previous studies, these issues, with the exception of speaker location, do not appear to account for the recent findings of Walden and Walden (2005). Using a single loudspeaker at 0° azimuth reproducing both talker and babble, Walden and Walden found that speech recognition in noise performance for one aided ear listening compared to two aided ear listening was superior in 82% (23 of 28) of adults. The participants ranged from 50 to 90 yr of age with a mean age of 75.1 yr. All participants presented with mild to moderately severe binaural symmetrical sensorineural hearing loss and had no known history of stroke, dementia, or other neurological disease. Of the 28 participants, 23 were experienced hearing aid users, and the remaining five were new hearing aid users. Speech recognition performance was measured using the Quick Speech-in-Noise (QuickSIN™; Killion et al, 2004) test.

One possible reason for the better performance Walden and Walden (2005) found with monaural amplification relates to the phenomenon known as binaural interference. Binaural interference is believed to be the result of the inappropriate fusion of the signals presented to the two ears (Arkebauer et al, 1971; Jerger et al, 1993; Chmiel et al, 1997). Indeed, there are data from case studies demonstrating that some older individuals perform more poorly on speech-in-noise tasks when wearing two hearing aids as compared to one (Hurley, 1993; Jerger et al, 1993; Chmiel et al, 1997; Carter et al, 2001; Holmes, 2003). Although Chmiel et al (1997) implied that binaural interference is a problem seen particularly with older adults, other investigators have reported binaural interference in younger patients (i.e., Arkebauer et al, 1971).

To access binaural interference, Walden and Walden (2005) used the Dichotic Digits Test (DDT; Musiek, 1983). In the DDT, different digits are presented to each ear, and the patient is either instructed to attend to and repeat all digits heard (i.e., free recall) or attend to and repeat words heard in only one ear (i.e., directed recall). In comparing results obtained in the directed recall condition with those obtained on the QuickSIN test, Walden and Walden (2005) found that DDT scores tended to be better in the ear with better speech-in-noise performance. Nonetheless, Jerger et al (1993) found an incidence of only 8–10% of patients who might be classified as experiencing binaural interference, in contrast to the 82% of subjects from Walden and Walden who performed poorer with two ears than one.

If binaural interference accounts for only a fraction of the Walden and Walden (2005) results, the question is whether or not there were methodological factors that might account for the findings. One possible factor was the fact that the unaided ear was left open and the presentation level of 70 dB HL meant the majority of the speech and noise cues were audible to the unaided ear. The audiometric data presented in Figure 1 of the Walden and Walden report suggest that 50% had less than a 60 dB hearing loss through 3000 Hz. Thus,

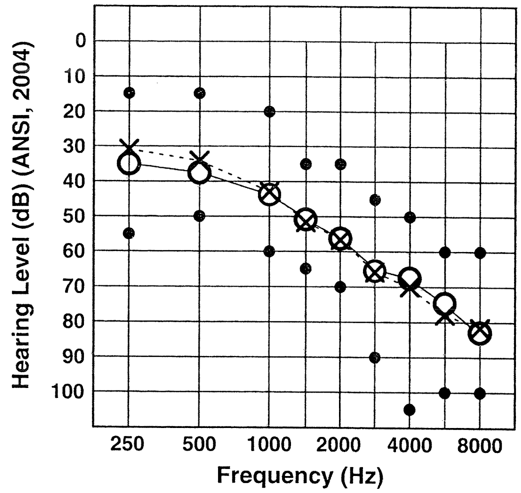

Figure 1. Mean audiogram for the right (open circles) and left ears (x's) of the participants. The filled circles above and below the audiogram line indicate the minimum and maximum threshold reported for each frequency.

in their "monaural" condition, the unaided ear would have received significant speech and noise cues.

One seemingly remote possibility is that the hearing aids were distorting at the 70 dB HL (82 dB SPL) input to the hearing aids. The peaks of such a signal exceed 95 dB SPL. This potential explanation has some appeal, only because in the binaural condition the participant would be receiving a distorted signal in both ears. Naidoo and Hawkins (1997) reported that subjects preferred two nondistorting hearing aids to one, but a single hearing aid was preferred when the hearing aids exhibited distortion at levels associated with social gatherings.

The Walden and Walden (2005) findings have such important implications that we decided to attempt to replicate their sound field study conditions in Experiment 1, adding a true monaural condition and an unaided condition for the single-loudspeaker presentation. In a second experiment, we further explored the benefit of two ears versus one, with diotic and binaural (dichotic) presentation over earphones using real-world restaurant binaural recordings. In particular, we compared a binaural recording made on the Knowles Electronics Manikin for Acoustic Research (KEMAR) manikin in a noisy restaurant with the left channel fed to both ears (diotic) or the left and right channel fed to the respective ears (dichotic, i.e., binaural).

METHODS

This prospective research study was approved by the Bay Pines VA Healthcare System Institutional Review Board. A single group of participants completed two experiments following the informed consent process. The order of the two experiments was counterbalanced across participants. In both experiments, a repeated measures design was used with test conditions randomized. Participants received a $10 check in the mail after the completion of the study to defray travel costs.

Participants

The 20 male listeners ranged in age from 59 to 85 yr old with a mean age of 75.5 yr (SD = 6.4 yr). For inclusion, all participants were experienced users of binaural hearing aids who were being fitted with new digital hearing aids. Previous hearing aid experience ranged from 2 mo to 9.2 yr with an average of 4.7 yr. All participants reported binaural hearing aid use on a daily basis. In addition, all participants exhibited binaural, symmetrical hearing losses as determined by between-ear air conduction threshold differences of no greater than 15 dB HL. Participants had no evidence of outer ear or middle ear pathology. All participants spoke English as a first language and had no known neurological or psychiatric disorders as determined by chart review. The average pure-tone air conduction threshold average (PTA) at 500, 1000, and 2000 Hz was 34.5 dB HL (SD = 8.0 dB). The pure-tone audiogram for both ears is shown in Figure 1.

Instrumentation

The speech stimulus was reproduced using a compact disc player (Sony, Model CDP-497) routed through an audiometer (Grason-Stadler, Model 61) to either a GSI Grason-Stadler loudspeaker (Experiment 1) or an ER-3A insert earphone (Experiment 2).

Experiment 1

The purpose of Experiment 1 was to replicate the Walden and Walden (2005) sound field study by measuring speech recognition in noise performance as a function of monaural versus binaural hearing aid use when both speech and noise originate from directly in front of the listener. Speech-in-noise performance was measured under five conditions: (1) right ear aided, left ear open; (2) left ear aided, right ear open; (3) both ears aided; (4) right ear aided, left ear plugged (true monaural); and (5) unaided. A true monaural condition was limited to a single ear to decrease the testing time. The right ear was selected for the true monaural condition because previous research suggests there is a right ear advantage for speech sounds (e.g., Lowe et al, 1970; Tadros et al, 2005).

Hearing Aids

Digital hearing aids from several manufacturers available through the Department of Veterans Affairs (VA) hearing aid contract were represented. All hearing instruments in this study were multichannel instruments with directional microphones, a feedback management system, and some form of a noise reduction algorithm. None of the hearing instrument features were disabled or deactivated during testing. With regard to directionality, the delivery of both the signal and the noise through the same speaker located at 0° azimuth was believed to preclude directionality from being a factor. Although it is possible that in some hearing aids, noise reduction was being activated, previous studies indicate that the use of currently available noise reduction algorithms does not result in improved speech understanding in noise (e.g., Dillon and Lovegrove, 1993; Abrams et al, 2007) but, rather, results in less annoyance from noise (Levitt, 2001) and reduced listener effort in noise (Sarampalis et al, 2009). In addition, it was believed that by allowing hearing aids to be programmed as they would be used in the real world, a more ecologically valid assessment of difference in speech recognition in noise performance, as a function of monaural versus binaural hearing aid fitting, would be obtained.

Prior to participating in the experiments, all subjects were fit with the new hearing aids to NAL-NL1 (Byrne et al, 2001) prescriptive target using real-ear verification measures. Real-ear insertion response (REIR) was measured with a 65 dB SPL input of digital speech noise with the listener seated 1 m from a speaker placed at 45° azimuth. The root mean square (rms) difference value between the prescribed target and measured REIRs was calculated at 500, 1000, 2000, 3000, and 4000 Hz, using the formula proposed by Byrne (1992). The rms calculation was used to measure the accuracy of the insertion gain curve in comparison with the prescribed target.

Byrne suggested that rms differences >3.1 dB would result in a perceptual difference for the hearing aid user. In calculating rms differences for the participants in this study, thresholds equal to or greater than 80 dB HL were not included in the rms analyses (n = 4) such that for four participants, 4000 Hz was omitted from the calculation based on threshold level. With 4000 Hz omitted for the four participants, all rms deviations from target were less than 3.1 dB.

In addition to assuring that the frequency-gain characteristics of the hearing aids were as close to prescriptive target as possible, the potential for amplified sounds to result in discomfort and/or distortion was assessed. Perception of discomfort was assessed by asking participants to rate the loudness of amplified sounds using the Hawkins et al (1987) approach. In this approach, participants were presented with an 85 dB SPL frequency sweep and asked to rate the loudness on a seven-point Likert scale with a 1 equal to "very soft" and a 7 equal to "uncomfortably loud." All reported ratings were 6 or lower with a median rating of 6 ("loud but OK") for the 20 participants. Finally, the electroacoustic performance of all the hearing aids was examined by using 2 cm^3 measures. All hearing aids were found to be functioning within specification with no evidence of excessive distortion.

Materials

The QuickSIN test (Killion et al, 2004) was used to assess speech recognition performance in noise. The QuickSIN test is a compilation of recorded sentences constructed by the Institute of Electrical and Electronics Engineers (IEEE) (1969). These sentences range from 7 to 12 syllables with syntactic context and moderate semantic context. The sentences are presented in multitalker babble at multiple signal-to-noise levels and recorded on a CD. Based on earlier data (McArdle and Wilson, 2006), Lists 1, 2, 3, 5, 6, 8, 9, 10, 11, and 12 of the QuickSIN materials were selected because of their homogeneity of performance for listeners with hearing loss. Each QuickSIN list contains six IEEE sentences spoken by a female with five target words per sentence. The level of the sentences is fixed, and the level of the multitalker babble, which is continuous throughout the list of sentences, varies in 5 dB increments resulting in a reduction of SNR from 25 to 0 dB S/N. The sentences are 2.5–3.0 sec in length with a 5–6 sec interval between sentences. Each list is approximately 55 sec in duration. Previous experience with the QuickSIN test (McArdle and Wilson, 2006) indicated that if the responses at the 5 dB S/N level were all incorrect, then the test could be terminated and the sentence at 0 dB S/N not presented.

Procedures

All testing for Experiment 1 was completed in sound field. The stimuli were presented from a single loudspeaker 3 ft from the participant at 0° azimuth. Each participant was tested in the following conditions: (1) right ear aided, left ear open; (2) left ear aided, right ear open; (3) both ears aided; (4) right ear aided, left ear plugged (true monaural); and (5) unaided. The first four conditions above were tested in random order followed by the unaided condition.

Standard QuickSIN administration procedures were utilized in these studies. The level of the QuickSIN sentences was fixed at 70 dB HL, and the level of the babble increased from 45 to 70 dB HL in 5 dB increments. Multiple lists were used to avoid any potential learning effect; thus, each QuickSIN list was presented only once for each listener. Practice lists were not administered as all participants were established patients at the Bay Pines VA Healthcare System and had been exposed to QuickSIN testing during previous clinic visits.

Participants were asked to respond verbally after each sentence. A total of two lists were presented and averaged for each condition to obtain the SNR loss for each condition tested. SNR loss represents the SNR required to obtain 50% correct for words in sentences and was established by subtracting the number of key words correctly repeated from 25.5. The "SNR loss" is relative to performance by listeners with normal hearing.

RESULTS AND PRELIMINARY DISCUSSION

The main question that prompted this study was whether two aided ears were better than one aided ear. The results of this study were that only 4 out of 20 (20%) performed better with a single hearing aid than with binaural hearing aids. This is similar to the 10% prevalence reported by Jerger et al (1993) but in contrast to the 82% reported by Walden and Walden (2005).

The individual data and mean SNR loss values are shown in Figure 2. In addition to the five test conditions mentioned above, the performance of the "best ear" is also indicated in Figure 2 to represent the best monaural performance regardless of whether it was right ear or left ear. Note that lower SNR loss values represent better speech recognition in noise performance. Figure 2 shows that the lowest mean SNR loss was found in the binaural condition (5.9 dB SNR), followed by the right ear aided condition (8.6 dB SNR); the left ear aided condition (9.3 dB SNR); and the true-monaural condition with the right ear aided, left ear plugged (10.3 dB SNR); and the highest mean SNR loss was observed in the unaided condition (12.6 dB SNR).

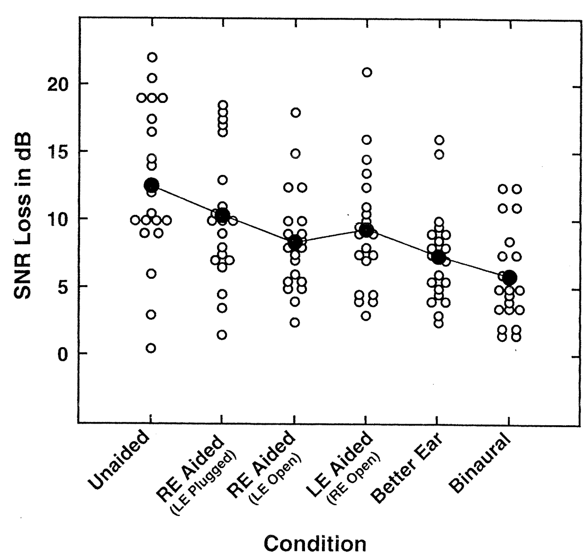

Figure 2. Average (large filled circle) and individual SNR loss for six conditions where a single loudspeaker at 0 degrees reproduced the talker and babble. Aided binaural listening provided better performance than the aided better ear (other ear open) for 16 of 20 subjects. The mean improvement of 1.5 dB between the two conditions as a single comparison was significant at the 95% confidence level, and similar to previous studies of two-ear vs. one-ear listening to a single source.

A repeated-measures version of the General Linear Model (GLM) analysis of variance (ANOVA) was used to further analyze the data. The main effect (listening condition) was found to be statistically significant [F (4, 76) = 13.08, $p < .001$], with an effect size estimate of approximately 41% of the variance in performance. Post hoc analyses using t-tests with a Bonferroni correction for multiple comparisons showed that the performance during the average binaural condition was significantly better resulting in lower SNR loss than the right ear aided, left ear aided, true-monaural, or unaided conditions. This main effect remained significant when adding years of use as a rescaled covariate (Algina, 1982) in the repeated measures analysis [$F(4,72) = 12.79$, $p < .001$].

The only other statistical difference in performance was for the right ear aided condition, which was significantly different (4.2 dB SNR better) than the unaided condition. Although the left ear aided condition was 3.3 dB SNR better than the unaided condition, this did not reach statistical significance. The fact that the difference between the unaided and left ear aided condition was not statistically significant ($p = .09$), whereas the difference between the unaided and the right ear aided was statistically significant, may be due to ear advantages for listening to speech. It is generally accepted that there is a "right ear" advantage for listening to speech because the language processing centers of the brain are for the majority of individuals in the left hemisphere and the crossed pathway is more efficient (Kimura, 1961). Seven of the 20 participants in the present study, however, performed better (less SNR loss) for the left ear aided condition than for the right ear aided condition. Six of the 28 participants from Walden and Walden (2005) also performed better (less SNR loss) in the left ear aided as compared to the right ear aided condition. In light of this finding, Walden and Walden examined their data by comparing performance in the binaural condition to data in a "best ear" condition.

To provide comparative data to those obtained by Walden and Walden (2005) the better single ear aided condition also is plotted in Figure 2. When the data for the unaided, binaurally aided, right ear aided (left ear plugged), and better ear aided conditions were examined using a repeated-measures version of the GLM ANOVA, the main effect of condition remained statistically significant [F (3, 57) = 19.1, $p < .001$] and partial eta-squared equaled 0.50, indicating that condition now accounts for 50% of the variance in performance. Post hoc analyses using t-tests with a Bonferroni correction for multiple comparisons showed that the performance during the average binaural condition was not statistically different from the better ear condition; however, performance in both the binaural and better ear condition was better than for either the true-monaural or unaided condition, which were not significantly different from each other. This finding suggests that as long as the "best" performing ear is aided, performance is similar to the binaural condition. Also implied is that performance in a truly monaural condition does not differ from performance in an unaided condition.

The main impetus for this study was to replicate Walden and Walden (2005) with the addition of a true monaural condition created by plugging the opposite unaided ear. Figure 3 is a bivariate plot of the true monaural condition plotted along the abscissa and the pseudo-monaural condition with the right ear aided (LE is open) plotted on the ordinate. The 95% confidence interval is show by the diagonal dashed lines. As can be seen in Figure 3, 6 of the 20 subjects showed a significant improvement in performance with an open left ear versus a closed left ear. Thus it does appear that a third of the participants were able to use the open ear to aid in recognition of the test stimuli, which does not support the labeling of the single aided ear with open opposite ear as a monaural condition.

Given that the mean audiogram in the current study (Fig. 1) is similar to the mean audiogram reported by Walden and Walden (2005, fig. 1), further analysis was completed to separate the participants with thresholds at all octave frequencies (250–8000 Hz) of 70 dB HL or better (better hearing) to those participants with thresholds greater than 70 dB HL (poorer hearing). As shown in Figure 4, the participants with poorer hearing on average improved almost 8 dB SNR with binaural hearing aids (6.3 dB SNR) as compared to the unaided condition (14.1 dB SNR), and improved 4.5 dB compared to the true-monaural right ear aided condition. The participants with better hearing improved as well; however,

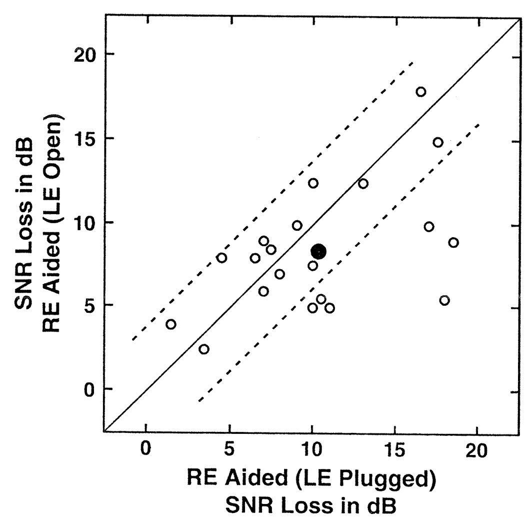

Figure 3. A bivariate plot of the individual data points (open circles) for the true monaural condition (RE aided, LE plugged) versus the monaural condition with RE aided, LE open, and the mean (large filled circle). The dotted diagonal lines represent the 95% confidence interval. Six of the 20 participants performed significantly worse with the LE plugged than when it was left open.

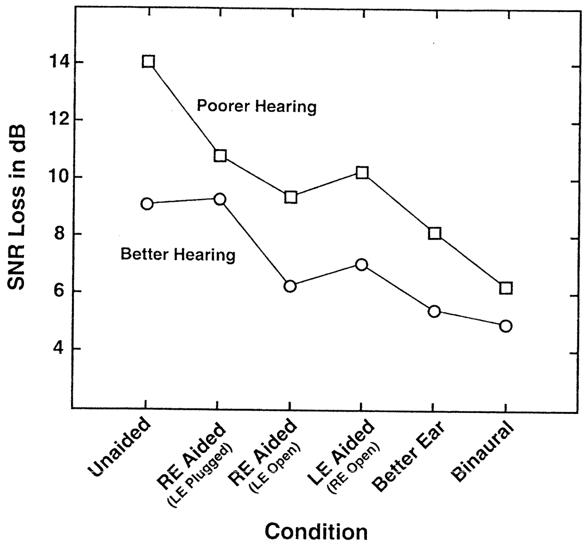

Figure 4. Average SNR loss for six conditions where a single loudspeaker at 0 degrees reproduced the talker and babble. The open squares represent the average performance of 14 listeners with poorer hearing whereas the open circles represent the average performance of the six listeners with better hearing.

the improvement was only about 4 dB SNR for binaural hearing aids (5 dB SNR) as compared to unaided (9.1 dB SNR), and 4.3 dB compared to the true-monaural right ear aided condition. Although the listeners with better hearing received half the improvement of those with poorer hearing, it is evident in Figure 4 that both groups of listeners performed better on a speech-in-noise task with binaural hearing aids than any other condition.

Taken as a whole, these findings support the use of binaural amplification for listening to speech in noise for the majority of listeners, especially for listeners with poorer hearing. Clearly these results are in contrast to those obtained by Walden and Walden (2005) and point to a need for further examination.

Experiment 2

The purpose of Experiment 2 was to further explore the effect of diotic versus binaural speech perception in noise by presenting two-channel recordings of speech-in-noise stimuli through insert earphones. The use of insert earphones eliminated any potential influences of hearing aid technology on performance and allowed for the presentation of two-channel information to mimic the binaural effects of real-world listening. Speech recognition performance in noise was assessed in four conditions: (1) monaural right, (2) monaural left, (3) diotic, and (4) binaural. The diotic condition involved the binaural recording made on the KEMAR manikin in a noisy restaurant with the left channel fed to both ears (diotic) whereas the binaural condition involved the left and right channel fed to the respective ears (dichotic). The participants were the same as in Experiment 1.

MATERIALS

The R-SPACE Quick Speech in Noise Test (RS-QSIN; Revit, pers. comm. 2008) was used to assess speech recognition in noise. The RS-QSIN is similar to the QuickSIN in that the stimuli are IEEE sentences that are presented in multitalker babble at multiple signal-to-noise levels. Each of the 18 tracks on the RS-QSIN CD contains a list of six IEEE sentences, each sentence having five target words. The level of the sentences are fixed, whereas the level of the restaurant babble, which is continuous throughout the list of sentences, is varied in increments of 5 dB, resulting in a reduction of SNR from 25 to 0 dB S/N (Christensen et al, 2002). The RS-QSIN was developed using the R-SPACE recording system, which consists of eight highly directional shotgun microphones that are placed in a circle to capture sounds from all horizontal directions, two feet from the listening position in the center of the circle. (Shotgun microphones, sometimes called line microphones, typically contain an array of microphone elements arranged to produce an exceptionally high directivity. Shotgun microphones are commonly used on football fields to pick up the voice of the quarterback).

Although the QuickSIN and the RS-QSIN are very similar, there are several differences. First, the RS-QSIN uses selected sentences from the first 360 IEEE sentences, as opposed to the QuickSIN, which uses sentences selected from the second 360 IEEE sentences. Second, the RS-QSIN uses spatially separated background noise from approximately 40 people in a busy restaurant whereas the QuickSIN utilizes four-talker babble. Last, the QuickSIN sentences were carefully made equivalent in intelligibility at each SNR based on extensive intelligibility measurements. The RS-QSIN sentences were equated in SNR based only on VU (volume unit) meter readings.

Compton et al (2004) compared the masking effect of that same restaurant noise (multitalker babble and silverware clinks in a busy restaurant) with the masking effect of a reproduction of the same noise in R-SPACE. To explain, the restaurant binaural recordings were made from the output of hearing aid microphones with the aids mounted on a KEMAR manikin. Simultaneously, eight-track recordings were made from eight shotgun microphones arrayed out from KEMAR's head. Compton et al made two sets of binaural recordings: (1) the live restaurant recordings described above and (2) reproduction in R-SPACE of the live shotgun microphone recordings. Compton et al found that subjects produced essentially identical 50% correct points with both sets of recordings. Given the previous success in simulating real-world conditions using RS-QSIN sound field presentations, without the random variability introduced by a true real-world environment, we used the RS-QSIN recordings to obtain binaural recordings for Experiment 2.

Specifically, we made the binaural recordings by placing a KEMAR in the center of an R-SPACE sound field at Etymotic Research. The KEMAR manikin was designed with a head, ears and torso that replicated the physical characteristics of the average adult (Knowles Electronics, 1978). For this experiment, the target sentences were delivered from 0° azimuth approximately 1 m in front of the KEMAR manikin. Simultaneously the uncorrelated restaurant noise was delivered through eight loudspeakers that were evenly placed surrounding KEMAR. Digital analog tape (DAT) recordings were made from the eardrum-position microphones in the head of the KEMAR manikin, preserving the binaural cues that can be received by a listener in a real-world setting when the target signal and the competing noise originate from different locations. A diffuse-field-inverse filter was used to produce the equivalent of free-field spectral balance in the KEMAR recordings (Killion, 1979).

Procedures

Each participant was tested, via insert earphones, in four conditions: (1) monaural right, (2) monaural left, (3) diotic, and (4) binaural. The order of conditions was randomized across participants. As in Experiment 1, standard QuickSIN administration procedures were utilized for the RS-QSIN scoring.

The level of the RS-QSIN sentences was fixed at 70 dB HL, following Walden and Walden, and the level of the babble varied from 45 to 70 dB HL in 5 dB increments. Multiple lists were used in order to avoid learning effects. Participants were asked to respond verbally after each sentence. Two lists were presented and averaged for each condition to derive the SNR required to get 50% correct for words in sentences.

RESULTS AND PRELIMINARY DISCUSSION

The individual data and mean performance of the 20 participants is shown for the four conditions in Figure 5. The binaural condition produced the best performance (10.4 dB SNR), followed by the diotic condition (12.4 dB S/N) and the two monaural conditions (14.7 dB and 14.9 dB S/N for R and L respectively). A repeated-measures version of the GLM ANOVA showed a statistically significant main effect of condition [F (3, 57) = 17.71, $p < .001$]. Post hoc analyses using t-tests with a Bonferroni correction for multiple comparisons indicated that mean performance in both the diotic and binaural conditions was significantly better than performance in either of the monaural conditions. In addition the mean SNR loss for the binaural condition was significantly lower, suggesting better performance than for the diotic condition.

Recall that in Experiment 2, participants were tested under insert earphones at 70 dB HL. Since the interaural attenuation for speech is at least 60 dB with insert earphones (Killion et al, 1985) and since none of the participants exhibited thresholds better than 15 dB, the procedure ensured a true monaural condition when the stimulus was routed only to one ear (either monaural right or monaural left). Since performance was better (i.e., lower 50% point) in both of the two binaural conditions (i.e., binaural and diotic) as compared to the two monaural conditions, it can be concluded that there is an advantage to understanding speech in noise using two ears rather than one ear.

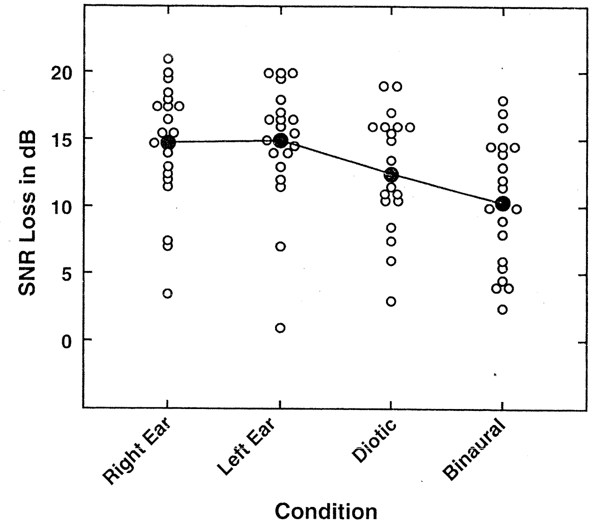

Figure 5. Average (large filled circle) and individual SNR loss for four earphone conditions. The binaural listening condition (two-channel recording) provided better performance than the diotic listening condition (single-channel recording).

Similar to the findings of Jerger et al (1993) but in contrast to Walden and Walden (2005), 80% of our subjects had better average scores in the binaural condition than either monaural condition. In fact, 65% of our participants had better scores in the *diotic* condition than in either ear.

These results support the findings obtained in Experiment 1, which showed that the best speech recognition in noise performance usually was obtained with binaural amplification. The finding of a statistically significant difference between the diotic and binaural condition, with the latter condition having the lowest SNR loss, supports the conclusion that not only is the use of two ears better than one ear but also that the availability of binaural cues further improves speech recognition in noise performance.

DISCUSSION

The present study was designed to examine whether speech-in-noise performance with binaural hearing aids was most often better than a single aid for adults with bilateral, symmetrical hearing loss. Two experiments were conducted. The first experiment was designed to replicate Walden and Walden (2005), whereas the second experiment was designed to further examine the monaural versus binaural controversy by utilizing a paradigm that preserved naturally occurring real-world binaural cues while eliminating any potential influences of hearing aid technology. In particular, all the signals in Experiment 2 were presented at 70 dB HL (85 dB SPL). As a reality check, the two comparable conditions in Experiment 1 (unaided frontal signal and noise in the sound field) and Experiment 2 (diotic earphone presentation of signal and noise—same sound in both ears) gave 12.6 dB and 12.4 dB, respectively. Both were presented at 70 dB HL.

The most important finding of the first experiment was that the best performance was obtained by 80% of our subjects in the binaurally aided condition. This finding of the present study is in contrast to the findings reported by Walden and Walden (2005), where only 18% of their participants performed better wearing two hearing aids as compared to one. On the other hand, Walden and Walden reported that the aided right ear condition was significantly better than the unaided condition. In this regard, the present experiment supports their findings.

Another important finding of the present study was that when the left ear was plugged, providing a true monaural condition, there was no longer a significant difference between unaided and the monaural right ear aided (LE plugged) condition. This result supports the premise that with 70 dB HL input, both the aided and unaided ears were contributing to performance in both the current study and Walden and Walden (2005).

In addition to examining the data as a function of the five sound field conditions (i.e., monaural right, monaural left, diotic, RE plugged/LE aided, and unaided), the data from Experiment 1 also were examined as a function of "best" monaural ear. When this examination was done, there was no longer a statistically significant difference between the diotic condition and the best monaural condition. As previously discussed, the lack of a difference between the diotic and best monaural condition (with the non-aided ear open) in conjunction with the finding that plugging the unaided ear results in a significant decrement in performance supports the conclusion that listening with two ears is better than one for understanding speech in noise even when there are no binaural head shadow cues to aid listening.

This conclusion that "two ears" are better than one was supported further by the results of the second experiment. In Experiment 2 participants were tested with insert earphones in order to not only further assess the benefits of binaural versus monaural listening but also to examine further the effects of the availability of binaural cues to speech recognition in noise performance. The fact that two ears listening to one signal performed better than either ear alone, and two ears listening to binaural cues performed even better, provided further support for the belief that two aids are most often better than one.

Clinical Implications

In addition to the current study, the most recent evidence (Walden and Walden, 2005; Henkin et al, 2007) suggests that in a laboratory setting, listeners with hearing loss on average perform better on a speech-in-noise task when input is received by both ears, even if the listener is only wearing one hearing aid. Thus, individuals with hearing loss who wear a single hearing aid in their "better" ear perform similarly to wearing two hearing aids as long as the speech is presented at a loud presentation level (70–90 dB SPL). In the current study it was shown that wearing two hearing aids in a real-world setting with binaural cues (Exp 2, binaural condition) does improve speech recognition performance in noise significantly more than aided listening with two ears to the same speech signal. This finding is somewhat supported by the results of Cox et al (2011), who found that participants who reported better real-world outcomes preferred to wear two hearing aids; however, Cox et al did report that 43 out of 94 participants preferred to use one hearing aid rather than two during a 12 wk field trial. Thus it can be said that even though the majority of listeners with hearing loss may perform better with binaural hearing aids in real-world listening situations, many of these listeners may not prefer the listening experience. Hearing aid patients may benefit from self-experimentation to determine the optimal configuration for them once prescribed hearing aids.

REFERENCES

Abrams H, Wilson R, McArdle R, Chisolm T. (2007) Randomized trial of the efficacy of digital noise reduction strategies: preliminary report. Paper presented at the American Auditory Society, Scottsdale, AZ, March 6.

Algina J. (1982) Remarks on the analysis of covariance in repeated measures designs. *Multivariate Behav Res* 17:117–130.

American National Standards Institute. (2004) *Specifications for Audiometers*. S3.6. New York: American National Standards Institute.

Arkebauer HJ, Mencher GT, McCall C. (1971) Modifications of speech discrimination in patients with binaural asymmetrical hearing loss. *J Speech Hear Disord* 36:208–212.

Belzile M, Markle DM. (1959) A clinical comparison of monaural and binaural hearing aids worn by patients with conductive and perceptive deafness. *Laryngoscope* 69:1317–1323.

Bronkhorst AW, Plomp R. (1988) The effect of head induced interaural time and level differences on speech intelligibility in noise. *J Acoust Soc Am* 83:1508–1516.

Byrne D. (1992) Key issues in hearing aid selection and evaluation. *J Am Acad Audiol* 3:67–80.

Byrne D, Dillon H, Ching T, Katsch R, Keidser G. (2001) NAL-NL1 procedure for fitting nonlinear hearing aids: characteristics and comparisons with other procedures. *J Am Acad Audiol* 12: 37–51.

Carhart R. (1946) Selection of hearing aids. *Arch Otolaryngol* 44: 1–18.

Carhart R. (1965) Problems in the measurement of speech discrimination. *Arch Otolaryngol* 82:253–260.

Carter A, Noe CM, Wilson RH. (2001) Listeners who prefer monaural to binaural hearing aids. *J Am Acad Audiol* 12: 261–272.

Chmiel R, Jerger J, Murphy E, Pirozzolo F, Tooley YC. (1997) Unsuccessful use of binaural amplification by an elderly person. *J Am Acad Audiol* 8:1–10.

Christensen L, Lelmink D, Soede W, Killion M. (2002) Complaints about hearing in noise: a new answer. *Hear Rev* 9:34–36.

Compton-Conley CL, Neuman AC, Killion MC, Levitt H. (2004) Performance of directional microphones for hearing aids: real-world versus simulation. *J Am Acad Audiol* 15:440–455.

Cox RM, Schwartz KS, Noe CM, Alexander GC. (2011) Preference for one or two hearing aids among adult patients. *Ear Hear* 32(2): 181–197.

Day G, Browning G, Gatehouse S. (1988) Benefit from binaural hearing aids in individuals with a severe hearing impairment. *Br J Audiol* 22:273–277.

DiCarlo L, Brown W. (1960) The effectiveness of binaural hearing for adults with hearing impairments. *J Aud Res* 1:35–76.

Dillon H. (2001) Binaural and binaural considerations in hearing aid fitting. In: Dillon H, ed. *Hearing Aids*. Turramurra, Australia: Boomerang Press, 370–403.

Dillon H, Lovegrove R. (1993) Single microphone noise reduction systems for hearing aids: a review and an evaluation. In: Studebacker GA, Hochberg I, eds. *Acoustical Factors Affecting Hearing Aid Performance*. Boston: Allyn and Bacon, 353–372.

Dirks D, Wilson R. (1969) The effect of spatially separated sound sources on speech intelligibility. *J Speech Hear Res* 12:5–38.

Durlach NI, Thompson CL, Colburn HS. (1981) Binaural interaction of impaired listeners: a review of past research. *Audiology* 20: 181–211.

Hawkins DB, Walden BE, Montgomery A, Prosek RA. (1987) Description and validation of an LDL procedure designed to select SSPL90. *Ear Hear* 8:162–169.

Hedgecock LD, Sheets BV. (1958) A comparison of monaural and binaural hearing aids for listening to speech. *AMA Arch Otolaryngol* 68:624–629.

Henkin Y, Waldman A, Kishon-Rabin L. (2007) The benefits of bilateral versus unilateral amplification for the elderly: are two always better than one? *J Basic Clin Physiol Pharmacol* 18(3): 201–216.

Hirsh IJ. (1948) Binaural summation and interaural inhibition as a function of the level of masking noise. *Am J Psychol* 61: 205–213.

Holmes AE. (2003) Binaural amplification for the elderly: are two aids better than one? *Int J Audiol* 42:63–67.

Hurley R. (1993) Monaural hearing aid effect: case presentations. *J Am Acad Audiol* 4:285–295.

Institute of Electrical and Electronics Engineers (IEEE). (1969) IEEE recommended practice for speech quality measurements. *IEEE Trans Audio Electroacoust* 17:227–246.

Jerger J, Dirks D. (1961) Binaural hearing aids, an enigma. *J Acoust Soc Am* 33:537–538.

Jerger J, Silman S, Lew H, Chmiel R. (1993) Case studies in binaural interference: converging evidence from behavioral and electrophysiologic measures. *J Am Acad Audiol* 4:122–131.

Killion MC. (1979) Equalization filter for eardrum-pressure recording using KEMAR manikin. *J Audio Eng Soc* 27:13–16.

Keys JW. (1947) Binaural versus monaural hearing. *J Acoust Soc Am* 19:629–631.

Killion MC, Niquette PA, Gudmundsen GI, Revit LJ, Banerjee S. (2004) Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *J Acoust Soc Am* 116:2395–2405.

Killion MC, Wilber LA, Gudmundsen GI. (1985) Insert earphones for more interaural attenuation. *Hear Instrum* 36:34–36.

Kimura D. (1961) Cerebral dominance and the perception of verbal stimuli. *Can J Psychol* 15(3):166–171.

Knowles Electronics. (1978) KEMAR Manikin measurement, *Proceedings of a conference organized by M.D. Burkhard,* Industrial Research Products, Inc.

Kochkin S. (2010) MarkeTrak VIII: customer satisfaction with hearing aids is slowly increasing. *Hear J* 63(1):11–19.

Kock WE. (1950) Binaural localization and masking. *J Acoust Soc Am* 22(6):801–804.

Koenig W. (1950) Subjective effects in binaural hearing. [Letter to the editor.] *J Acoust Soc Am* 22:61–62.

Levitt H. (2001) Noise reduction in hearing aids: an overview. *J Rehabil Res Dev* 38:111–121.

Lowe SS, Cullen JK, Berlin CI, Thompson CL, Willett ME. (1970) Perception of simultaneous dichotic and monotic monosyllables. *J Speech Hear Res* 13:812–822.

MacKeith NW, Coles RA. (1971) Binaural advantages in hearing speech. *J Laryngol Otol* 85:213–232.

Markle DM, Aber WA. (1958) Clinical evaluation of monaural and binaural hearing aids. *AMA Arch Otolaryngol* 67:606–608.

McArdle R, Wilson RH. (2006) Homogeneity of the 18 QuickSIN Lists. *J Am Acad Audiol* 17(3):157–167.

Mencher GT, Davis A. (2006) Binaural or monaural amplification: is there a difference? A brief tutorial. *Int J Audiol* 45:S3–S11.

Musiek FE. (1983) Assessment of central auditory dysfunction: the dichotic digit test revisited. *Ear Hear* 4:79–83.

Naidoo SV, Hawkins DB. (1997) Monaural/binaural preferences: effect of hearing aid circuit on speech intelligibility and sound quality. *J Am Acad Audiol* 8:188–202.

Olsen WO, Carhart R. (1967) Development of test procedures for evaluation of binaural hearing aids. *Bull Prosthet Res* 10: 22–49.

Ross M. (1980) Binaural versus monaural hearing aid amplification for hearing impaired individuals. In: Libby ER, ed. *Binaural Hearing and Amplification*. Chicago: Zenetron, 1–21.

Sarampalis A, Kalluri S, Edwards B, Hafter E. (2009) Objective measures of listening effort: effects of background noise and noise reduction. *J Speech Lang Hear Res* 52(5):1230–1240.

Stearns WP, Lawrence DW. (1977) Binaural fitting of hearing aids: when to and when not, how does one decide? *Hear Aid J* 30:51–53.

Tadros SF, Frisina ST, Mapes F, Kim S, Frisina DR, Frisina RD. (2005) Loss of peripheral right-ear advantage in age-related hearing loss. *Audiol Neurootol* 10(1):44–52.

Walden TC, Walden BE. (2005) Monaural versus binaural amplification for adults with impaired hearing. *J Am Acad Audiol* 16: 574–584.

Wright HN, Carhart R. (1960) The efficiency of binaural listening among the hearing-impaired. *Arch Otolaryngol Head Neck Surg* 72:789–797.