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Sentence Recognition in Noise and Perceived Benefit of Noise Reduction on the Receiver and Transmitter Sides of a BICROS Hearing Aid

Kristi Oeding*
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Abstract

Background: In the past, bilateral contralateral routing of signals (BICROS) amplification incorporated omnidirectional microphones on the transmitter and receiver sides and some models utilized noise reduction (NR) on the receiver side. Little research has examined the performance of BICROS amplification in background noise. However, previous studies examining contralateral routing of signals (CROS) amplification have reported that the presence of background noise on the transmitter side negatively affected speech recognition. Recently, NR was introduced as a feature on the receiver and transmitter sides of BICROS amplification, which has the potential to decrease the impact of noise on the wanted speech signal by decreasing unwanted noise directed to the transmitter side.

Purpose: The primary goal of this study was to examine differences in the reception threshold for sentences (RTS in dB) using the Hearing in Noise Test (HINT) in a diffuse listening environment between unaided and three aided BICROS conditions (no NR, mild NR, and maximum NR) in the Tandem 16 BICROS. A secondary goal was to examine real-world subjective impressions of the Tandem 16 BICROS compared to unaided.

Research Design: A randomized block repeated measures single blind design was used to assess differences between no NR, mild NR, and maximum NR listening conditions.

Study Sample: Twenty-one adult participants with asymmetric sensorineural hearing loss (ASNHL) and experience with BICROS amplification were recruited from Washington University in St. Louis School of Medicine.

Data Collection and Analysis: Participants were fit with the National Acoustic Laboratories' Nonlinear version 1 prescriptive target (NAL-NL1) with the Tandem 16 BICROS at the initial visit and then verified using real-ear insertion gain (REIG) measures. Participants acclimatized to the Tandem 16 BICROS for 4 wk before returning for final testing. Participants were tested utilizing HINT sentences examining differences in RTS between unaided and three aided listening conditions. Subjective benefit was determined via the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire between the Tandem 16 BICROS and unaided. A repeated measures analysis of variance (ANOVA) was utilized to analyze the results of the HINT and APHAB.

Results: Results revealed no significant differences in the RTS between unaided, no NR, mild NR, and maximum NR. Subjective impressions using the APHAB revealed statistically and clinically significant benefit with the Tandem 16 BICROS compared to unaided for the Ease of Communication (EC), Background Noise (BN), and Reverberation (RV) subscales.

Conclusions: The RTS was not significantly different between unaided, no NR, mild NR, and maximum NR. None of the three aided listening conditions were significantly different from unaided performance as has been reported for previous studies examining CROS hearing aids. Further, based on comments from

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participants and previous research studies with conventional hearing aids, manufacturers of BICROS amplification should consider incorporating directional microphones and independent volume controls on the receiver and transmitter sides to potentially provide further improvement in signal-to-noise ratio (SNR) for patients with ASNHL.

Key Words: Asymmetric sensorineural hearing loss, bilateral contralateral routing of signals (BICROS), hearing aid, noise reduction, reception threshold for sentences (RTS)

Abbreviations: APHAB = Abbreviated Profile of Hearing Aid Benefit; ASNHL = asymmetric sensorineural hearing loss; AV = Aversiveness of Sounds; BICROS = bilateral contralateral routing of signals; BN = Background Noise; CROS = contralateral routing of signals; EC = Ease of Communication; HINT = Hearing in Noise Test; HRPO = Human Research Protection Office; MIL = most intelligible level; NAL-NL1 = National Acoustic Laboratories' Nonlinear version 1 prescriptive target; NR = noise reduction; REIG = real-ear insertion gain; RTS = reception threshold for sentences; RV = Reverberation; SNR = signal-to-noise ratio; SRT = speech reception threshold; SSQ = Speech, Spatial, and Qualities of Hearing Questionnaire; USNHL = unilateral sensorineural hearing loss; WRS = word recognition score

Patients with unilateral sensorineural hearing loss (USNHL), which is defined as unaidable hearing loss in one ear and normal hearing in the opposite ear, and asymmetric sensorineural hearing loss (ASNHL), which is defined as unaidable hearing loss in one ear and aidable hearing loss in the opposite ear, have unique disadvantages communicating compared to patients with normal hearing or bilateral symmetrical hearing loss. Patients with USNHL or ASNHL do not have the advantages that binaural hearing provides, which include eliminating the head shadow effect (Tillman et al, 1963), maintaining the squelch effect (Markides, 1977; Gulick et al, 1989), binaural summation, and improved localization. Patients with USNHL and ASNHL have great difficulty recognizing speech when the signal arrives to the poorer ear, recognizing speech in background noise when noise arrives to the better ear, and localizing sound.

Fowler (1960) initially introduced contralateral routing of signals (CROS) and bilateral contralateral routing of signals (BICROS) amplification to help alleviate the problems associated with the head shadow effect and listening in background noise. CROS was developed for patients with USNHL, while BICROS was developed for patients with ASNHL. This study focuses on patients with ASNHL and the potential benefit provided by BICROS for these patients. The original purpose of BICROS was to improve the ability of patients with ASNHL to hear sounds originating on the poorer ear side (i.e., eliminate the head shadow effect). This was accomplished by placing a microphone in or over the poorer ear (transmitter side), which then transmits and amplifies the signal from the poorer ear to a hearing aid with a microphone, amplifier, and receiver on the better ear (receiver side) (Harford, 1966). This allows patients with ASNHL to achieve improved speech recognition regardless of which side the speech signal originates.

Patients with ASNHL often develop strategies to situate themselves so the "wanted" signal is on the side of the better ear, and when able to do so, the patient typically performs quite well while also avoiding situations where noise is on the side of the better ear and the signal is on the side of the poorer ear. Constantly having to scan the listening environment so the better ear is toward the signal and the poorer ear is toward the noise, however, can be fatiguing. BICROS amplification can assist a patient in regaining the speech signal missing from the poorer ear side (i.e., eliminate the head shadow effect). When noise is on the transmitter side, however, the noise is amplified and transferred to the better ear, which could interfere with the wanted signal.

Unfortunately, few peer-reviewed studies are available examining the efficacy and effectiveness of speech recognition with BICROS amplification in background noise. In one study, Del Dot et al (1992) examined whether significant differences exist in speech recognition with the BICROS transmitter turned on or off with speech from 0° and four-talker babble noise from 135° and 225°. Differences in the speech reception threshold (SRT), which is the signal-to-noise ratio (SNR) at which sentences can be repeated correctly in noise 50% of the time, were examined with input levels of the noise at 40 and 60 dB SPL. Results revealed a mean improvement in SRT with the transmitter turned on, compared to off, by 4.3 dB ($p < 0.01$) and 3.4 dB ($p < 0.001$) when the background noise levels were at 40 and 60 dB SPL, respectively. This result indicates that the presence of the BICROS transmitter can provide significant benefit when the transmitter is on versus off in background noise when speech arrives from the front and noise from behind.

Although studies on the effectiveness of BICROS amplification are limited, numerous studies have examined the efficacy and effectiveness of CROS amplification. Results from studies on CROS amplification would be expected to be similar to BICROS amplification because the primary purpose of both amplification strategies is to eliminate the head shadow effect. Studies examining CROS amplification have utilized a variety of loudspeaker arrays, including speech and noise from 0° (Niparko et al, 2003; Wazen et al, 2003;

Hol et al, 2004; Lin et al, 2006), noise from 0° and speech from ±90° (Bosman et al, 2003; Hol et al, 2004, 2005), speech from 0° and noise from ±90° (Niparko et al, 2003; Wazen et al, 2003; Hol et al, 2004, 2005; Lin et al, 2006), or speech to the better ear and noise to the poorer ear or vice versa (Lotterman and Kasten, 1971). These studies report that CROS amplification performed better than unaided when noise was presented to the side of the better ear and speech was presented to the side of the poorer ear. When noise, however, was presented to the side of the poorer ear and speech to the side of the better ear, CROS consistently performed poorer than unaided. Poorer performance occurs because the transmitter transfers the unwanted amplified noise to the hearing aid on the better ear, which amplifies the noise and results in interference with the unamplified wanted speech signal. While CROS amplification effectively eliminates the head shadow effect, speech recognition in noise remains problematic.

Harford and Dodds (1974) recognized this drawback of CROS amplification and recommended incorporating an on-off switch on the transmitter side to allow patients to turn off the transmitter in difficult listening environments. Other options include incorporating independent volume controls on the receiver and transmitter sides or a remote control to reduce the gain or turn off the transmitter. These options, however, require the patient to auditorily scan the environment and remember to make the appropriate decision. Another solution could be the presence of noise reduction (NR) on the receiver and transmitter sides to assist in attenuating amplification if an unmodulated signal (noise) is detected. This feature could resolve the problem addressed above because the offside transmitting microphone would provide greater gain if the processor detected a modulated signal (speech) and reduced gain if an unmodulated signal (noise) is detected.

Until recently, BICROS amplification has only been available with an omnidirectional microphone and/or NR on the receiver side. The only option for the listener to improve performance in noise was a volume control, if available, or turning off the transmitter so a directional microphone could be activated on the receiver side (i.e., a monaural fit). To address this problem, Unitron (Plymouth, MN) introduced a CROS/BICROS hearing aid (Tandem 16) where programmable multichannel NR is available on the receiver *and* transmitter sides in 16 frequency channels. While most previous studies have reported no significant improvement in speech recognition in noise for conventional hearing aids when NR is activated (Boymans and Dreschler, 2000; Alcantara et al, 2003; Nordrum et al, 2006; Bentler et al, 2008), the Tandem 16 BICROS presents a unique application. Unlike these previous studies, all speech and noise signals are being processed by one ear, and one hearing aid serves to transfer the signal from one ear to the other. As mentioned earlier, the primary

purpose of the transmitter is to transfer the wanted speech signal from the side of the poorer ear to the side of the better ear. When noise, however, is present alone or combined with speech on the transmitter side, the noise is amplified and transferred to the side of the better ear and may degrade the audibility of the wanted speech signal. The addition of NR on the transmitter side could provide an improvement in speech recognition by attenuating the noise transferred from the side of the poorer ear that interferes with the wanted speech signal, which could improve the SNR at the better ear. In this manner, what was "easier" in an unaided condition remains possibly easier in an aided condition (signal on the better side; primarily noise on the poorer side) as the activation of NR on the transmitter side may help attenuate some of the unwanted noise. Currently, no peer-reviewed studies have examined the effectiveness or efficacy of NR in BICROS amplification to determine if participants obtain improved speech recognition or improved perceived listener benefit when listening in noise. In addition, no study has examined the performance of BICROS amplification using a diffuse loudspeaker array with 65 dB SPL "real-world" uncorrelated restaurant noise.

This study examined two null hypotheses:

1. No significant differences in the reception threshold for sentences (RTS, in dB), which is the SNR at which sentences can be repeated correctly in noise 50% of the time, for Hearing in Noise Test (HINT) sentences (Nilsson et al, 1994) presented in a diffuse listening environment are present between unaided, no NR, mild NR, or maximum NR on the receiver and transmitter sides of the Tandem 16 BICROS hearing aid.
2. No significant differences exist between unaided and aided problem scores on the Ease of Communication (EC), Background Noise (BN), and Reverberation (RV) subscales of the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire (Cox and Alexander, 1995).

MATERIALS AND METHODS

Participants

Twenty-one participants were recruited from the patient database of the Division of Adult Audiology at Washington University in St. Louis School of Medicine via personal communication in the clinic, telephone, or a letter approved by the Human Research Protection Office (HRPO). Each participant signed an Informed Consent Form approved by HRPO either prior to or at the initial visit. To qualify for entrance into the study, each participant was required to (a) have worn BICROS amplification for at least 4 wk, (b) have an ASNHL, defined as unaidable hearing in the poorer ear (profound

sensorineural hearing loss, poor word recognition [less than 40%], and/or an inability to tolerate amplified sounds) and a word recognition score (WRS) of 60–100% at the most intelligible level (MIL) in the better ear, (c) be at least 18 yr of age, and (d) be a native English speaker. Participants were excluded if (a) they did not meet the inclusion criteria, (b) were nonambulatory, (c) had a history of chronic or terminal illness, and/or (d) could not commit to the time requirements of the study.

Otoscopy, pure-tone audiometry (250 to 8000 Hz in octave and midoctave frequencies), and WRS testing, utilizing the compact disc recording of the female version of the Northwestern University Auditory Test No. 6 (NU-6) (Tillman and Carhart, 1966) word lists presented at the participant's MIL were performed to determine if he/she qualified for the study. The MIL was determined using monitored live voice presentation (voice peaking at 0 dB on the VU meter) by talking to the participant and asking the participant to indicate when the presentation level was most intelligible and at a comfortably loud level. An *a priori* power analysis utilizing G*Power 3.0.10 (http://www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3) determined that 25 participants were required to determine statistical significance using data from Valente et al (2006), a two-tailed test, an alpha of 0.05, and power of 0.80. A concurrent sample size calculation after data were collected for 15 participants revealed that 21 participants would be sufficient to determine statistical significance based on a two-tailed test, an alpha of 0.05, and power of 0.80.

Mean hearing thresholds (dB HL) in the better and poorer ear and ±1 SD are reported in Figure 1. Ten participants had better hearing in the right ear and 11 in the left ear. The average hearing thresholds revealed a slight to severe sensorineural hearing loss in the better ear and a severe to profound sensorineural hearing loss in the poorer ear. The mean WRS was 88.0% (SD = 7.5%) for the better ear and 5.7% (SD = 11.1%)
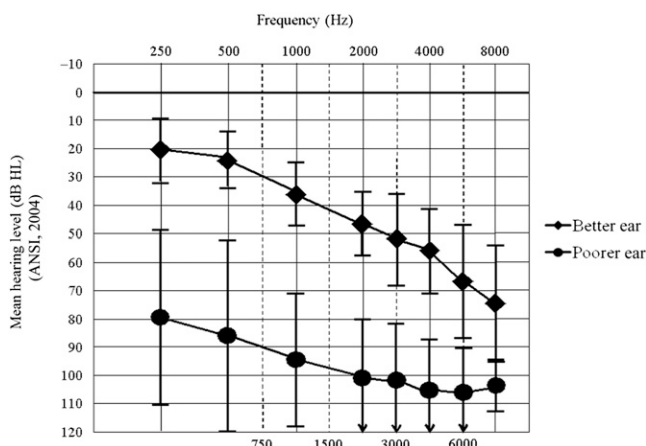

Figure 1. Audiogram reporting the mean and ±1 SD for hearing thresholds (dB HL) in the better ear (♦) and poorer ear (●). Arrows indicate SDs beyond the limits of the audiogram.

for the poorer ear. Twelve participants were male and nine were female with a mean age of 72.9 yr (SD = 8.4 yr). Etiology in the poorer ear included Ménière's disease (n = 4), acoustic neuroma (n = 4), congenital deafness (n = 4), sudden idiopathic sensorineural hearing loss (n = 6), noise induced hearing loss (n = 2), and severe acute otitis media (n = 1). The mean duration of hearing loss was 24.9 yr (SD = 20.9 yr).

The participants' mean years of experience with BICROS amplification was 8.1 yr (SD = 5.5 yr). Table 1 reports the BICROS model and years of experience with BICROS amplification. At the time of entrance into the study, 18 participants wore BICROS amplification, and three wore monaural amplification in the better ear. All three participants wearing monaural amplification had worn BICROS amplification several years and had experience with the advantages and disadvantages of using BICROS amplification. One wore BICROS amplification for 11.0 yr and decided to discontinue use of the BICROS due to constant repairs to the receiver and transmitter because of poor moisture resistance and wore a monaural hearing aid for one year. The second participant wore BICROS amplification for 15.3 yr and had worn monaural amplification for nine months because the transmitter was damaged and purchasing another transmitter was prohibitive. The third participant wore BICROS amplification for 6.9 yr before using monaural amplification for eight years because of a positive experience with a loaner monaural hearing aid during repair of the participant's BICROS and improved perceived benefit in noise with monaural amplification.

Hearing Aid Fitting and Verification

In this study, the Unitron Tandem 16 BICROS hearing aid was investigated. This hearing aid features NR that can be activated on the receiver *and* transmitter sides and contains 16 frequency bands for programming adjustments. The Tandem 16 has four settings of NR that can be programmed for the receiver *and* transmitter. These settings include no NR and mild ($\sim$−3 dB SPL), moderate ($\sim$−5 to −6 dB SPL), and maximum NR ($\sim$−8 to −9 dB SPL). The NR algorithm analyzes the input signal in each of the 16 channels using three criteria: (a) modulation depth, (b) modulation frequency, and (c) signal duration. The NR algorithm has an overall sampling cycle of 320 times per second, and when noise is the prominent signal in a channel, gain/output is decreased in that specific frequency channel(s). The attack time, when measured using white noise with an input of 85 dB SPL, is approximately 2000 msec, and the release time is approximately 40 msec. These time constants can vary depending on the input signal characteristics, level, and frequency. The magnitude of NR does not change as input level changes and is based upon the estimated SNR in a

Table 1. Current or Previous BICROS Amplification Worn by Participants and Years of Experience

Participant	Manufacturer	Model	Years of Experience
1	Phonak	Eleva 311 BTE + CROSLink BTE	2.4
2	Phonak	Savia 211 BTE + CROSLink BTE	3.0
3	Phonak	Savia 211 BTE + CROSLink BTE	18.0
4	Interton	IQ Quantum CM WLXX ITE to ITE	6.4
5	Widex	Mind 440-9 BTE + Wired Satellite Side BTE	11.4
6	Phonak	Versata M BTE + CROSLink BTE	11.0
7	Phonak	Eleva 211 BTE + CROSLink BTE	13.3
8	Phonak	Extra 211 BTE + CROSLink BTE	13.8
9	Phonak	Valeo 211 BTE + CROSLink BTE	10.7
10	Phonak	Eleva 211 BTE + CROSLink BTE	4.3
11	Phonak	Savia 211 BTE + CROSLink BTE	14.5
12	Telex	Act II CR BTE to BTE	6.9
13	Phonak	Eleva 211 BTE + CROSLink BTE	3.9
14	Unitron	Conversa NT ITE + WiFi Mic ITE	3.3
15	Phonak	Savia 211 BTE + CROSLink BTE	11.0
16	Phonak	Nios Micro V BTE + CROSLink BTE	2.1
17	Phonak	Savia 211 BTE + CROSLink BTE	15.3
18	Phonak	Eleva 211 BTE + CROSLink BTE	4.5
19	Phonak	Audeo S Smart V RIC + CROS BTE	0.7
20	Phonak	Versata P BTE + CROSLink BTE	13.6
21	Phonak	Audeo S Smart V RIC + CROS BTE	0.3

Note: BTE = behind-the-ear; ITE = in-the-ear; RIC = receiver-in-the-canal.

specific frequency channel, which significantly varies by the spectrum of the noise and speech signal. (John Pumford, pers. comm.).

Prior to the hearing aid fitting, performance of the receiver to the ANSI S3.22-1996 standard (American National Standards Institute [ANSI], 1996) was verified electroacoustically using a Frye© Fonix® 6500-CX hearing aid analyzer. In addition, the transmitter side was verified by placing the transmitter at the test point inside the test box and connecting the receiver side to an HA-2 coupler placed on top of the test box on a foam cushion. Then a 70 dB SPL speech-weighted composite signal was presented in the test box to confirm transmission between the two devices. In addition, the receiver and transmitter were measured on the Audioscan® Verifit® Model VF-1 hearing aid analyzer to ensure that NR was operating correctly (see Fig. 2). For this measure, the receiver was connected to an HA-2 coupler and placed at the test point in the test box. Then "air conditioner" noise was presented at 65 dB SPL, and the NR settings were measured. For the transmitter side, the receiver was coupled to the HA-2 coupler and held outside, but near, the test box, and the transmitter was placed at the test point inside the test box. The air conditioner noise was again presented at 65 dB SPL, and each NR setting was verified. The overall root-mean-square level of NR was calculated from these measures. As an example, in Figure 2A, the no NR (upper curve), mild NR (middle curve), and maximum NR (lower curve) conditions overall had a reduction in noise of 0, 4, and 8 dB SPL (see NR box to the far

right), respectively, for the receiver, and in Figure 2B a reduction in noise of 0, 2, and 6 dB SPL, respectively, for the transmitter. The investigators tested the Tandem 16 BICROS using dual pink noise and the International Speech Test Signal using a +9 dB SNR to determine that NR was activated to determine how the presence of speech affected the activation of NR after the study was complete. NR was activated on the receiver and transmitter sides at a +9 dB SNR. The NR decreased output more in the low frequencies than in the high frequencies. Results revealed a 0–1 dB SPL decrease in output for the mild and maximum NR compared to no NR and revealed a 1–3 dB SPL decrease in output for mild NR and 2–5 dB SPL decrease in output for maximum NR in the low to mid-frequencies compared to no NR on the receiver and transmitter, respectively, for a +9 dB SNR.

Each hearing aid was preprogrammed with three programs in a randomized order with (a) no NR, (b) mild NR, and (c) maximum NR to examine the effects of the extreme ends of the available NR settings. The NR "aggressiveness" of both the receiver and transmitter sides of the Tandem 16 can only be programmed equally (e.g., both have mild NR). The features of phase canceller (feedback manager) and datalogging remained enabled, but Anti-Shock, Wind Noise Manager, Auto-Pro 3 (automatic program), and Speech Enhancement LD were disabled. All three programs were programmed the same and had the same features activated, with the only difference being the magnitude of NR. If the participant qualified for the study after the audiometric evaluation, he or she was fit with the Tandem 16
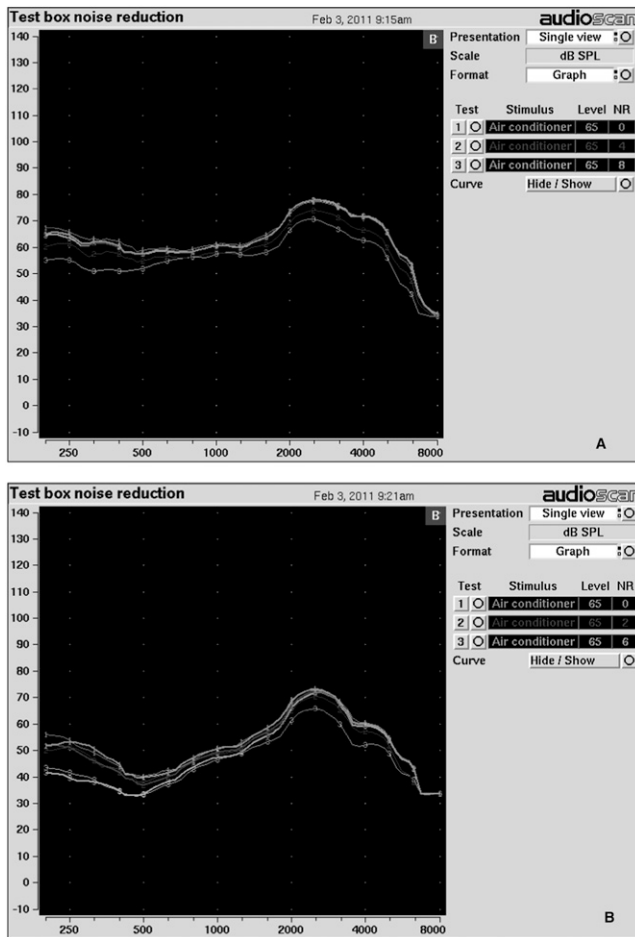
Figure 2. Example of NR testing using the Verifit hearing aid analyzer on the receiver *(A)* and transmitter *(B)* sides using air conditioner noise presented at 65 dB SPL. In both *A* and *B,* the upper curve represents no NR, the middle curve mild NR, and the lower curve maximum NR. Overall NR for each condition is reported in the box to the right.

BICROS. If the participant's earmolds provided a poor fit, earmold impressions were made to order new earmolds, and the participant returned in 2 wk for the hearing aid fitting. Otherwise, if the participant's earmolds were deemed appropriate, he or she was fit at the initial visit.

First, a feedback test was performed followed by the transmission optimization test, which was completed using the fitting software per manufacturer's instructions to ensure the receiver and transmitter communication was optimal. Prior to real-ear verification, the National Acoustic Laboratories' Nonlinear version 1 prescriptive target (NAL-NL1; Byrne et al, 2001) was corrected for 16 channels and 0° loudspeaker placement using the corrections available in the Frye 8000. This corrected target was then manually entered into the target menu on a Frye 6500 hearing aid analyzer. The Tandem 16 BICROS was fit using a Frye 6500 hearing aid analyzer with real-ear insertion gain (REIG) measures using the corrected NAL-NL1 prescriptive target (Fig. 3). The features were left activated in the

hearing aid and the signal, 65 dB SPL speech-weighted composite noise, was very quickly turned on and off to prevent NR from attenuating the signal.

The goal of the fitting was to adjust the REIG to match the NAL-NL1 target within ±5 dB to 2000 Hz and ±10 dB to 4000 Hz. As can be seen in Figure 3, mean measured REIG at seven discrete octave and interoctave frequencies from 500 to 8000 Hz were within ±5 dB, except for 6000 Hz, which was within ±10 dB. The participant's own BICROS or monaural hearing aid (for three participants) REIG was also verified via real-ear measures using the NAL-NL1 target corrected for the number of channels in the respective hearing aid (6 to 20 channels) and azimuth (0°) using a 65 dB SPL speech-weighted composite noise (Fig. 4). This measure was completed on 16 participants because two participants' BICROS hearing aids were being repaired, and three participants did not bring their own BICROS to the clinic to complete testing. All features remained activated, and the signal was again quickly turned on and off to prevent an attenuation of the signal. The mean participant's own BICROS or monaural hearing aid (≤5 dB at 500, 2000, and 3000 Hz and ≤10 dB at 1000 and 4000–8000 Hz) did not match the NAL-NL1 target as closely as the Tandem 16 (≤5 dB at 500–4000 and at 8000 Hz and ≤10 dB at 6000 Hz). The differences may be due to subtle decreases in hearing thresholds over time and not compensating for these changes in hearing levels or programming limitations of the hearing aid. The mean measured REIG is, however, within ±10 dB at all seven discrete octave and interoctave test frequencies.

The performance of the transmitter microphone on the Tandem 16 was verified by performing a real-ear aided response (REAR) measurement using a 65 dB SPL speech-weighted composite noise at 90° to the side of the better ear. Then a second measure was completed at 270° on the transmitter side to verify that sound was being transmitted from the side of the poorer ear to the side of the better ear (see Pumford, 2005, for more details). Finally, loudness judgments were completed for a speech-weighted composite noise at 50 ("soft"), 65 ("comfortable"), and 80 dB SPL ("loud, but OK"), and adjustments, if necessary, were made to the overall output based on participant report.

Each participant was counseled on how to use the volume controls on the receiver and transmitter sides, use the program button, open and close the battery doors, change batteries, and place the hearing aids in his or her ears. Each participant was encouraged to press the program button to change the three programs in noisy listening environments to determine which program(s) he or she preferred. Datalogging was examined at the final visit, and only a small number of participants switched between programs, while the majority remained in Program 1 for the 4 wk. A follow-up phone
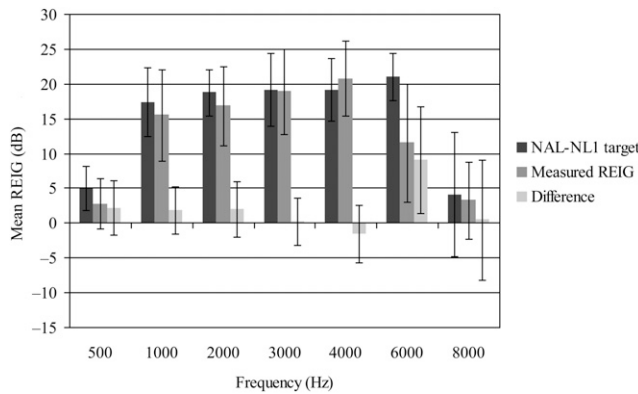
Figure 3. Mean REIG and ±1 SD for the prescribed NAL-NL1 target, measured REIG, and difference for the Tandem 16 BICROS for a 65 dB SPL speech-weighted composite noise from 500 to 8000 Hz at seven discrete octave and interoctave frequencies. Note that the NAL-NL1 target was corrected for the number of channels (16) in the hearing aid and azimuth (0°).

Figure 4. Mean REIG and ±1 SD for the prescribed NAL-NL1 target, measured REIG, and difference for the participant's own BICROS for a 65 dB SPL speech weighted composite noise from 500 to 8000 Hz at seven discrete octave and interoctave frequencies. Note that the NAL-NL1 target was corrected for the number of channels in the respective hearing aid (6 to 20 channels) and azimuth (0°), and this measure was only completed for 16 participants.

call was completed at 1 wk to ensure each participant was performing well with the Tandem 16. If fine-tuning was needed, the participant returned for fine-tuning and wore the Tandem 16 for 4 wk before returning for final testing; otherwise participants returned in 3 wk after the phone call for final testing. Prior to final testing, the Tandem 16 BICROS was dehumidified, a new battery was inserted in the receiver and transmitter, and electroacoustic analysis and NR performance were measured and compared with initial analyses to ensure the Tandem 16 BICROS was working properly.

R-Space™ System

The R-Space™ system consists of eight Boston Acoustics CR-65 loudspeakers in a circular array, with each loudspeaker separated by 45° in a 1.97 × 2.54 × 2.73 m double-walled sound suite (volume = 14.05 m³) with a reported reverberation time of 0.19 sec (Industrial Acoustics Company, pers. comm.). The radius of the circle was 2 ft plus the depth of the loudspeaker (200 mm) (see Oeding et al, 2010, for a detailed description of the R-Space system, calibration, and recording of the uncorrelated restaurant noise). HINT sentences were presented from the front loudspeaker, and uncorrelated Lou Malnati's restaurant noise was presented from all eight loudspeakers to create a diffuse noise sound field. A lavaliere microphone was placed near the participant so the examiner could hear the participant's responses. The R-Space system was calibrated each day prior to final testing.

Hearing in Noise Test (HINT)

The HINT consists of 250 sentences (25 lists of 10 sentences per list) read by a male speaker that are of approximately equal length (six to eight syllables) and difficulty (first-grade reading level) and have been digitally
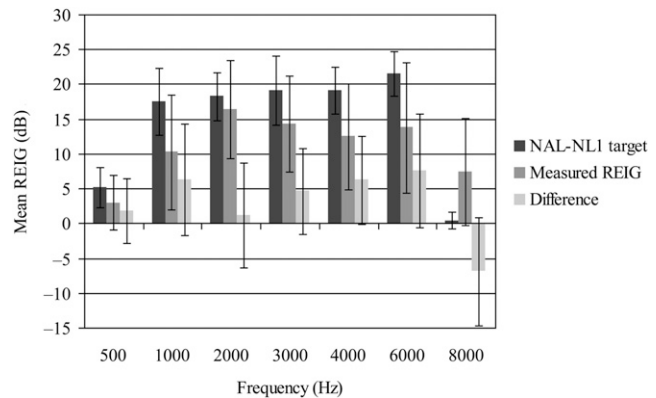
recorded for standardized presentation. The first 240 sentences (24 lists) were utilized in this study. The HINT uses an adaptive step procedure to estimate the RTS at which sentences, embedded in uncorrelated restaurant noise, could be repeated correctly 50% of the time. The administration of the HINT required presentation of four lists (40 sentences) for each of the four experimental conditions (for a detailed description of the procedures for administering the HINT, see Oeding et al, 2010).

A randomized block repeated measures design was utilized in which each participant was tested with each of the four treatment levels of unaided, no NR, mild NR, and maximum NR. The Tandem 16 BICROS was placed in the respective program with the hearing aid off the participant's ear, blinding the participant to the current program of use, and the volume control was rotated to "three" on the receiver and transmitter sides. Two participants were evaluated with the volume control at "two and a half" on the transmitter side and "three" on the receiver side due to loudness discomfort. The four treatment levels of unaided, no NR, mild NR, and maximum NR were counterbalanced to prevent order effects. The participant was seated in the center of the R-Space system facing the front (0°) loudspeaker, and head placement was level with the loudspeakers. Each participant was instructed to face the dot in the center of the front loudspeaker throughout the entire test session and told that sentences would arrive from the front loudspeaker and 65 dB SPL uncorrelated restaurant noise would arrive from all eight loudspeakers. Participants were asked to repeat the sentence exactly as heard and, if unsure, take a guess. A HINT RTS (in dB) was measured for each of the four treatment levels and HINT sentence lists were counterbalanced for each participant. The test session was approximately 45 min in length. At the end of the study, participants were compensated $100 for

participation or had the option to purchase the Tandem 16 BICROS at a significantly reduced cost.

Abbreviated Profile of Hearing Aid Benefit (APHAB)

The APHAB is a questionnaire that measures a participant's perception of how well he or she performs in 24 listening environments divided into four subscales (six listening environments per subscale): EC, BN, RV, and Aversiveness of Sounds (AV). A participant rates how much difficulty he or she has in each environment on a seven-point assessment scale when unaided and aided. The resulting aided problem score (in %) is subtracted from the unaided problem score to determine the magnitude of benefit the participant perceives from the aided condition compared to unaided. The APHAB was completed at the final visit via interview to prevent confusion for the unaided and aided listening conditions.

RESULTS

Hearing in Noise Test (HINT)

The mean RTS (dB) and ±1 SD for each listening condition (unaided, no NR, mild NR, and maximum NR) is reported in Figure 5. A higher RTS indicates poorer performance as the participant required a higher SNR to repeat the sentences correctly 50% of the time. Minimal differences in mean RTS were noted between the four listening conditions with a mean RTS of 8.0 dB (SD = 3.8 dB) for the unaided condition, a mean of 9.4 dB (SD = 2.5 dB) for no NR, a mean of 9.2 dB (SD = 3.0 dB) for mild NR, and a mean of 8.6 dB (SD = 3.0 dB) for maximum NR.

A one-way repeated measures analysis of variance (ANOVA) was completed to determine if significant differences were present between the four listening conditions. Results revealed no significant differences between unaided, no NR, mild NR, and maximum NR (F(3, 60) = 2.5, p = 0.07). Therefore, the null hypothesis was accepted.
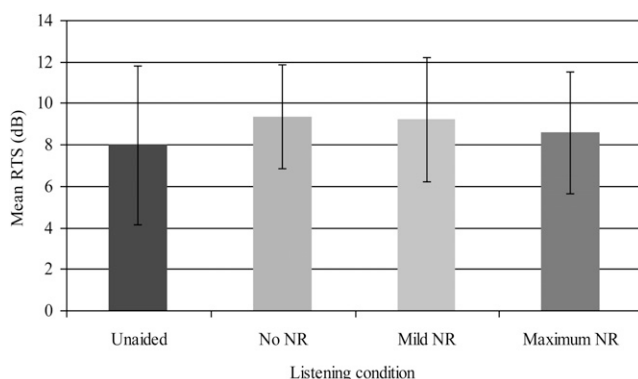
Figure 5. Mean RTS (in dB) and ±1 SD for each listening condition. Note that a higher RTS indicates poorer performance in background noise.

Abbreviated Profile of Hearing Aid Benefit (APHAB)

The mean unaided and aided Tandem 16 problem scores, the resulting benefit scores, and ±1 SD are reported in Figure 6 for the EC, BN, and RV subscales. The results on the AV subscale were not included because this subscale has been reported not to be as clinically relevant as the EC, BN, and RV subscales (Cox and Alexander, 1995). A repeated measures ANOVA was performed for each subscale comparing unaided and aided (Tandem 16) problem scores. Results revealed significant differences between unaided and aided problem scores for the EC (F(2, 40) = 30.6, p < 0.001), BN (F(2, 40) = 34.4, p < 0.001), and RV (F(2, 40) = 68.2, p < 0.001) subscales.

Participants' perceived improved mean benefit with the Tandem 16 for the EC (Mean = 30.9%; SD = 21.5%), BN (Mean = 32.4%; SD = 24.6%), and RV (Mean = 40.7%; SD = 21.8%) subscales. Bonferroni-adjusted pairwise comparisons revealed significant improved perceived performance with the Tandem 16 for the EC (p < 0.001), BN (p < 0.001), and RV (p < 0.001) subscales. Therefore, the null hypothesis stated previously was rejected and the alternative hypothesis that significant differences exist between unaided and aided problem scores on the EC, BN, and RV subscales of the APHAB was accepted. According to Cox and Alexander (1995), the benefit scores are also clinically significant for a 90% critical difference.

DISCUSSION

Results from the present study revealed no significant differences between unaided, no NR, mild NR, and maximum NR. Unaided performance provided the
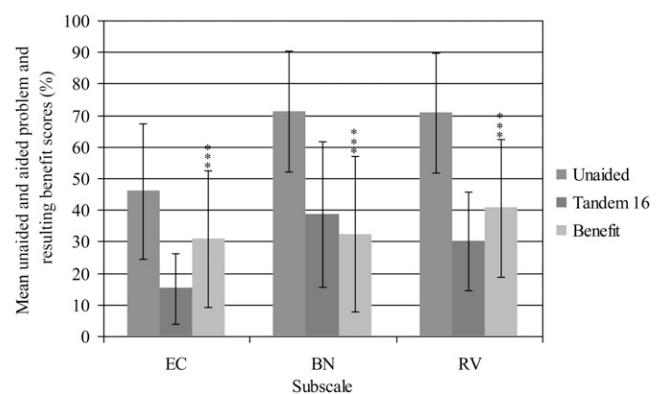
Figure 6. Mean problem scores and the resulting benefit scores (%) and ±1 SD for the EC, BN, and RV APHAB subscales for the unaided and aided listening conditions. A higher problem score indicates more perceived problems, and a positive benefit score indicates improved perceived benefit for the Tandem 16. Three asterisks indicates p < 0.001.

lowest (best) RTS (Mean = 8.0 dB; SD = 3.8 dB), followed by maximum NR (Mean = 8.6 dB; SD = 3.0 dB), mild NR (Mean = 9.2 dB; SD = 3.0 dB), and no NR (Mean = 9.4 dB; SD = 2.5 dB). Maximum NR resulted in a mean RTS improvement of 0.8 dB compared to when NR was deactivated, which was not significant. This agrees with previous studies (Boymans and Dreschler, 2000; Alcantara et al, 2003; Bentler, 2005; Ricketts and Hornsby, 2005; Nordrum et al, 2006; Bentler et al, 2008) that examined the effectiveness of NR in conventional hearing aids using different NR algorithms in various loudspeaker arrays. These arrays included speech and noise from 0° (Alcantara et al, 2003), speech from 0° and noise from 180° (Bentler et al, 2008), speech from 0° and noise from 90, 180, and 270° (Boymans and Dreschler, 2000; Nordrum et al, 2006), and speech from 0° and noise from 60, 160, 180, and 300° (Ricketts and Hornsby, 2005). Results revealed no significant differences when NR was activated or deactivated (Boymans and Dreschler, 2000; Alcantara et al, 2003; Bentler, 2005; Ricketts and Hornsby, 2005; Nordrum et al, 2006; Bentler et al, 2008). Results from studies that examined differences in SNR when the NR was activated or deactivated reported mean changes of approximately −2 to 2 dB, with a negative SNR indicating better performance with NR deactivated (Boymans and Dreschler, 2000; Alcantara et al, 2003; Nordrum et al, 2006; Bentler et al, 2008). The results from the current study are in agreement with the middle of this range.

When the results of the current study are compared to previous studies investigating CROS amplification, it is interesting to note differences between CROS and unaided performance compared to differences between the Tandem 16 BICROS and unaided. Results from previous studies examining CROS and unaided with speech from 0° and noise on the transmitter side reveal better unaided performance compared to CROS by an average of 2.5 to 4.1 dB SNR (Niparko et al, 2003; Hol et al, 2004, 2005; Lin et al, 2006). In the current study, however, participants, on average, performed equally well in either of the three aided BICROS listening conditions relative to unaided listening, while using a more difficult diffuse listening environment. That is, participants in the current study performed better when compared to previous studies using CROS amplification considering the listening environment in the current study was considerably more difficult and results of the three aided conditions were not significantly poorer than unaided.

The differences, however, between the results from the current study and results from previous studies are difficult to assess due to variations in methodology (differences in speech materials, loudspeaker arrangements, etc.), but it can be hypothesized why the results were different. One significant difference between the current study and previous studies investigating CROS amplification is the degree of hearing loss in the better ear. That is, participants using CROS have normal or near normal hearing in the better ear, while BICROS participants have poorer hearing in the better ear. This results in CROS participants having lower (better) unaided SNRs than participants using BICROS. This better SNR for CROS participants will result in greater differences between unaided and aided performance than BICROS participants who, due to the greater hearing loss in the better ear, will result in a smaller difference between unaided and aided performance. Another difference involves the fitting and verification of hearing aid performance. Past studies did not report real-ear measures of CROS performance; therefore, the validity of the hearing aid fit cannot be determined. Another possibility are differences in hearing aid technology (ability to amplify soft speech; quality of signal from transmitter; etc.) that were not examined in this study.

While the findings of the current study did not reveal objective benefit, subjective preference was reported. The mean APHAB benefit score on the EC, BN, and RV subscales revealed that the Tandem 16 was statistically and clinically better than unaided. Several studies have examined APHAB problem and benefit scores of CROS hearing aids (Bosman et al, 2003; Niparko et al, 2003; Wazen et al, 2003; Hol et al, 2004, 2005). These studies reported unaided problem scores of 16.7–29.0% for EC, 67.6–74.0% for BN, and 37.7–50.0% for RV, and CROS aided problem scores of 12.0–20.0% for EC, 48.0–56.0% for BN, and 30.5–40.0% for RV (Bosman et al, 2003; Hol et al, 2004, 2005). Unaided problem scores from the current study were close to the high end of the range or greater for the EC (46.0%), BN (71.8%), and RV (70.8%) subscales, which is probably related to the greater difficulty due to greater hearing loss in the better ear compared to normal or near normal hearing for CROS users. Aided problem scores for the Tandem 16 were 15.1% for EC, 38.7% for BN, and 30.1% for RV. Relative to past CROS studies, the average aided EC problem score is similar to the average problem score reported for CROS; the average BN problem score is significantly lower than the average problem score reported for CROS; and the average RV problem score in the current study is on the lower end reported for CROS. This indicates that BICROS aided problem scores were similar to or slightly better than previous CROS studies. This is promising as this indicates that BICROS participants achieve perceived performance in the real world that is equal to or slightly better than CROS users that have normal or near normal hearing in the better ear. Due to the higher problem scores for unaided and essentially equal or slightly improved aided problem scores, benefit scores were greater for BICROS participants in the current study (EC = 32.4%; BN = 32.4%; RV = 40.7%)

than CROS users (EC = 0.6–7.6%; BN = 5.9–21.1%; RV = 2.5–9.6%) in past studies (Bosman et al, 2003; Niparko et al, 2003; Wazen et al, 2003; Hol et al, 2004, 2005). One reason for the slightly better benefit scores reported in the current study (Fig. 6) may be related to the verification of the Tandem 16 BICROS, which may have led to improved speech recognition because past studies examining CROS amplification did not verify the fitting using real-ear measures.

A second reason for the higher (better) mean aided problem scores may be the improved signal processing of the Tandem 16 BICROS compared to past technology that was not examined in this study (improved feedback management, NR, amplification of soft speech, improved programming capabilities, etc.). Hill et al (2006) evaluated participant satisfaction with recent CROS (wired) and BICROS amplification (both wired and wireless models) via a proprietary questionnaire investigating satisfaction with the participant's device. Of the 91 participants, 61 retained his or her device (67%). While Hill et al (2006) did not specify the models of the newer technology or whether the devices were fit using real-ear measures, the acceptance rate was higher than those reported in the past (anecdotally, in the clinic of the authors, the acceptance rate for CROS in the past was ~10%) (Valente, 2007). Another reason for perceived improvement could be the participant's ability to control the volume independently on the receiver and transmitter sides, allowing the user to decrease unwanted noise from the transmitter side, which was mentioned by several participants

While it is possible to conclude that the lack of agreement between the objective measure (i.e., no improvement in performance for the BICROS with NR on or off) and the subjective measure (preference, as measured by the APHAB) is exclusively related to the Hawthorne or placebo effect (Bentler et al, 2003; Dawes et al, 2011), an alternative explanation might help explain this seemingly contradictory finding. The lack of agreement between objective and subjective measures has a long history when investigating hearing aid performance (Valente et al, 1998; Cord et al, 2000; Hallgren et al, 2005; Ricketts and Hornsby, 2005; Oeding and Valente, 2013). Consider for this study, for which the participant wore the experimental hearing aid for 4 wk and the objective measures were completed in approximately 1 hr, the average result revealed no significant differences in noise between NR on or off. As stated earlier, this is not a novel finding and has been reported numerous times in the past. The reader, however, needs to keep in mind that each participant wore the experimental hearing aids for 4 wk. To globally conclude that the preference for the experimental device was exclusively related to the placebo effect might, in the opinion of the authors, be a little shortsighted. It is possible that a participants' subjective preference

for the experimental device was not at all related to performance in noise as these were experienced users and probably already have grown to not expect improvement of recognizing speech in noise (Kochkin, 2000; Kochkin, 2002a, 2002b). Rather, other untested factors provided by the Tandem BICROS during the 4 wk in which the participants used the aids may be of greater importance to the participant. For example, it is possible that the Tandem 16 BICROS was less noisy; allowed the participant to better hear his or her spouse, friends, or grandchildren; had greater flexibility to control the volume on each side; provided a smoother frequency response, wider bandwidth, improved feedback management, improved sound quality, "naturalness" of sound, greater audibility (Tandem providing improved REIG of 5.4 dB at 1000 Hz, 4.5 dB at 3000 Hz, and 8.2 dB at 4000 Hz) as reported in Figures 3 and 4, and improved ease of listening; and so on. That is, it is possible that the seemingly contradictory finding between objective and subjective measures may not be exclusively related to the dependent variable (differences in performance for speech in noise) but may be related in part to other subjective judgments not evaluated in this study. Also, it is possible that the outcome measures used to assess differences were not sufficiently sensitive to assess additional factors that may be important to the typical BICROS user.

Since the start of this study, another BICROS system was introduced that for the first time allows the directional microphone to be activated when the hearing aid is in the BICROS mode. Williams et al (2012) compared the new Phonak BICROS system to participants' current BICROS using the Words-in-Noise (WIN) test (Wilson, 2003) and the Speech, Spatial, and Qualities of Hearing Questionnaire (SSQ) (Gatehouse and Noble, 2004). Unaided and both BICROS systems were measured using monosyllabic words from 0° and multitalker babble from 180° and with the signal presented to the poorer ear and noise to the better ear and vice versa for both BICROS systems. A repeated measures ANOVA revealed a significant main effect ($p < 0.001$), but post hoc analysis did not reveal any significant differences between the Phonak and the participants' BICROS ($p > 0.05$). While the Phonak BICROS had better SNR thresholds, Williams et al (2012) attributes this to the investigators' inability to match the NAL-NL1 target with the participants' BICROS due to less programming ability compared to the Phonak BICROS. The SSQ revealed significant improvement for the Phonak BICROS for several subscales in the speech, spatial, and quality domains. These results are similar to the current study as the objective results were not significant, but the subjective results were. The speech recognition results also contrast with past studies examining directional microphones in conventional hearing aids.

When past research reporting the effectiveness of NR upon speech recognition in noise is examined, studies evaluating the efficacy of NR *and* directional microphones consistently report an improved SNR with the use of a directional microphone alone compared to NR alone with little added benefit when a directional microphone and NR are combined (Boymans and Dreschler, 2000; Ricketts and Hornsby, 2005; Nordrum et al, 2006). In two studies, SNR differences between a directional microphone alone, NR alone, and directional microphone plus NR were examined (Boymans and Dreschler, 2000; Nordrum et al, 2006) and reported an average improved SNR of 3.3 to 4.0 dB for the directional microphone alone compared to NR alone and an improvement of −0.2 to 0.2 dB for the directional microphone compared to the directional microphone plus NR (a negative value indicates improved performance for the directional microphone plus NR condition). Therefore, based on these previous studies, the addition of a directional microphone could improve SNR, while the addition of NR could improve perceived comfort in noise. Based on the results of the current study and previous studies, it is felt that manufacturers of CROS/BICROS hearing aids should consider offering independent volume controls on the receiver and transmitter sides, NR on both sides for potentially *greater comfort* in noisy listening environments, and directional microphones on the receiver *and* transmitter sides for potentially improved performance in noise.

CONCLUSIONS

Results from the present study did not reveal significant differences in RTS between unaided, no NR, mild NR, or maximum NR on the receiver and transmitter sides for the Tandem 16 BICROS while measuring speech recognition in diffuse noise. Participants, however, perceived statistically and clinically significant benefit with the Tandem 16 compared to unaided performance on the EC, BN, and RV subscales of the APHAB. At the final visit seven participants purchased the Tandem 16, three preferred the Tandem 16 but did not purchase the Tandem 16 (major reasons cited were due to a recent purchase of a new BICROS and cost of the Tandem 16), and 11 participants preferred their current hearing aid. Additional features, such as independent volume controls on the receiver and transmitter sides, and directional microphones included on the receiver *and* transmitter sides need to be considered by hearing aid manufacturers and evaluated to determine if adults with ASNHL can obtain an improved SNR, similar to adults with bilateral SNHL. BICROS technology has been shown to overcome the head shadow effect and provide benefit for speech on the side of the poorer ear. The next step is to investigate solutions, such as those described above, to help patients achieve greater speech recognition in noise.

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