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J Am Acad Audiol 21:546–557 (2010)

Effectiveness of the Directional Microphone in the Baha® Divino™

DOI: 10.3766/jaaa.21.8.6

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Abstract

Background: Patients with unilateral sensorineural hearing loss (USNHL) experience great difficulty listening to speech in noisy environments. A directional microphone (DM) could potentially improve speech recognition in this difficult listening environment. It is well known that DMs in behind-the-ear (BTE) and custom hearing aids can provide a greater signal-to-noise ratio (SNR) in comparison to an omnidirectional microphone (OM) to improve speech recognition in noise for persons with hearing impairment. Studies examining the DM in bone anchored auditory osseointegrated implants (Baha), however, have been mixed, with little to no benefit reported for the DM compared to an OM.

Purpose: The primary purpose of this study was to determine if there are statistically significant differences in the mean reception threshold for sentences (RTS in dB) in noise between the OM and DM in the Baha® Divino™. The RTS of these two microphone modes was measured utilizing two loudspeaker arrays (speech from 0° and noise from 180° or a diffuse eight-loudspeaker array) and with the better ear open or closed with an earmold impression and noise attenuating earmuff. Subjective benefit was assessed using the Abbreviated Profile of Hearing Aid Benefit (APHAB) to compare unaided and aided (Divino OM and DM combined) problem scores.

Research Design: A repeated measures design was utilized, with each subject counterbalanced to each of the eight treatment levels for three independent variables: (1) microphone (OM and DM), (2) loudspeaker array (180° and diffuse), and (3) better ear (open and closed).

Study Sample: Sixteen subjects with USNHL currently utilizing the Baha were recruited from Washington University's Center for Advanced Medicine and the surrounding area.

Data Collection and Analysis: Subjects were tested at the initial visit if they entered the study wearing the Divino or after at least four weeks of acclimatization to a loaner Divino. The RTS was determined utilizing Hearing in Noise Test (HINT) sentences in the R-Space™ system, and subjective benefit was determined utilizing the APHAB. A three-way repeated measures analysis of variance (ANOVA) and a paired samples *t*-test were utilized to analyze results of the HINT and APHAB, respectively.

Results: Results revealed statistically significant differences within microphone ($p < 0.001$; directional advantage of 3.2 dB), loudspeaker array ($p = 0.046$; 180° advantage of 1.1 dB), and better ear conditions ($p < 0.001$; open ear advantage of 4.9 dB). Results from the APHAB revealed statistically and clinically significant benefit for the Divino relative to unaided on the subscales of Ease of Communication (EC) ($p = 0.037$), Background Noise (BN) ($p < 0.001$), and Reverberation (RV) ($p = 0.005$).

Conclusions: The Divino's DM provides a statistically significant improvement in speech recognition in noise compared to the OM for subjects with USNHL. Therefore, it is recommended that audiologists

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Portions of this manuscript were presented at the annual meeting of the American Auditory Society, March 2009, Scottsdale, AZ, and at AudiologyNOW!, April 2010, San Diego, CA.

Cochlear Americas provided the TU-1000 skull simulator, Baha Divinos on loan, and monetary compensation for subject participation.

This publication was made possible by Grant Number UL1 RR024992 and Sub-Award Number TL1 RR024995 from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research.

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consider selecting a Baha with a DM to provide improved speech recognition performance in noisy listening environments.

Key Words: Abbreviated Profile of Hearing Aid Benefit (APHAB), bone anchored hearing aid (Baha), directional microphone, reception threshold for sentences (RTS), single sided deafness, unilateral sensorineural hearing loss

Abbreviations: APHAB = Abbreviated Profile of Hearing Aid Benefit; AV = Aversiveness; Baha = bone anchored auditory osseointegrated implant (bone anchored hearing aid); BN = Background Noise; BTE = behind-the-ear; CROS = contralateral routing of the signal; DM = directional microphone; EC = Ease of Communication; FBR = front-to-back ratio; FDA = Food and Drug Administration; HINT = Hearing in Noise Test; MIL = most intelligible level; OM = omnidirectional microphone; PTA = pure-tone average; RTS = reception threshold for sentences (in dB); RV = Reverberation; SLM = Quest 1900 Precision sound level meter; SNR = signal-to-noise ratio; USNHL = unilateral sensorineural hearing loss; WRS = word recognition score

The bone anchored auditory osseointegrated implant (bone anchored hearing aid, or Baha®) has been approved for persons with unilateral sensorineural hearing loss (USNHL) since 2002. The Food and Drug Administration (FDA, 2002) defines USNHL as normal hearing thresholds in one ear (pure-tone air conduction average [PTA] ≤20 dB HL at 500, 1000, 2000, and 3000 Hz) and sensorineural hearing loss in the opposite ear (profound sensorineural hearing loss, poor word recognition, and/or an inability to tolerate amplified sound) (Valente, 2007).

Since the Baha's application for USNHL, numerous studies have examined the efficacy (or laboratory performance) and effectiveness (or "real-world" performance) of the Baha. These studies have focused on listening in noise as this is one of the most difficult listening environments patients with USNHL encounter. The omnidirectional microphone (OM) of the Baha in particular has been extensively studied in noise utilizing objective and subjective measures compared to unaided and contralateral routing of the signal (CROS) hearing aids (Bosman et al, 2003; Niparko et al, 2003; Wazen et al, 2003; Hol et al, 2004; Hol et al, 2005; Baguley et al, 2006) or to unaided alone (Andersen et al, 2006; Newman et al, 2008; Dumper et al, 2009; Yuen et al, 2009). Various loudspeaker arrays have been utilized in these studies. Most studies have examined listening conditions in which speech and noise were presented from 0°, lateralized speech (noise presented from 0° and speech presented to either the better or poorer ear), and/or lateralized noise (speech presented from 0° and noise presented to either the better or poorer ear). Additional research has also examined listening conditions where speech was presented to the poorer ear and noise was presented to the better ear (Newman et al, 2008; Yuen et al, 2009), where speech was presented from 0° and noise from 180° (Yuen et al, 2009), and a diffuse listening environment with speech presented from 0° and noise from 45°, 135°, 225°, and 315° (Newman et al, 2008).

Results from these studies have reported, in general, an advantage for the Baha compared to CROS and/or unaided for speech and noise from 0°, lateralized noise to the better ear, lateralized speech to the better and poorer ear, and speech presented to the poorer ear and noise presented to the better ear. Unaided, however, performed consistently better than Baha and CROS when speech was presented from 0° and noise was presented to the poorer ear (Niparko et al, 2003; Wazen et al, 2003; Hol et al, 2004, 2005; Dumper et al, 2009). It is hypothesized that performance decreased because the Baha and CROS amplified the noise on the poorer side causing interference with the speech signal being heard in the better ear. Also, unaided has the advantage of the head shadow effect in this listening situation as the noise signal is attenuated by approximately 6 dB (Tillman et al, 1963) when it reaches the better ear, whereas the Baha and CROS amplify the noise. One feature that could improve the performance of the Baha for users with a USNHL in noisy listening environments is a directional microphone (DM).

There have been a small number of studies comparing the efficacy, such as speech recognition in various loudspeaker arrays, and effectiveness, such as benefit questionnaires, of the DM in the Baha Compact™ and/or Divino™ to OM (Hodgetts, 2005; Lin et al, 2006; Kompis et al, 2007; Linstrom et al, 2009), CROS (Lin et al, 2006), and unaided performance (Kompis et al, 2007; Linstrom et al, 2009). These studies examined the DM in subjects with bilateral conductive and/or mixed hearing losses (Hodgetts, 2005; Kompis et al, 2007) or subjects with USNHL (Lin et al, 2006; Linstrom et al, 2009). Results for speech presented from 0° and noise presented to the poorer ear revealed OM performance equal to or poorer than unaided, DM performance equal to or slightly poorer than unaided, and DM performance slightly better than OM (Hodgetts, 2005; Lin et al, 2006; Linstrom et al, 2009). Kompis et al (2007) investigated speech presented from 0° and noise presented from 180° and reported statistically significant benefit of approximately 7–8 dB with the Compact OM and Divino OM and DM compared to unaided. When OM was compared to DM performance, a statistically significant directional advantage of 2.3 dB was reported for the Divino DM compared to

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the Compact OM. No statistically significant directional advantage (approximately 1 dB) was reported for Divino DM compared to the Divino OM. These results contrast with previous studies comparing conventional behind-the-ear (BTE) and custom hearing aids, which have consistently reported a statistically significant advantage for DMs compared to OMs (Valente et al, 1995; Pumford et al, 2000; Valente et al, 2000; Amlani, 2001).

The DM in the Compact and Divino utilizes a hypercardioid polar pattern, with deep nulls at 110° and 260° and 100° and 260°, respectively, and a mildly attenuated lobe at 180° (Microtronic, 2000; Sonion, 2005). Therefore, the listening conditions reported in the past may not have allowed the full advantage provided by the nulls of the DM in the Compact and Divino. Also, while these studies examined one difficult situation that persons with USNHL encounter, listening to speech from the poorer side, none of these studies examined the performance of the DM in a more "real-world" listening condition where noise is diffuse (i.e., surrounding the patient).

The primary purpose of this study, therefore, was to determine if statistically significant differences were present in the reception threshold for sentences (RTS, in dB) in noise for Hearing in Noise Test (HINT) sentences (Nilsson et al, 1994) between

1. The Divino's OM and DM, averaged across loudspeaker array and better ear;
2. Two loudspeaker arrays: when HINT sentences were presented from 0° and noise was presented from either 180° (behind the subject) or a diffuse field (from 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°), averaged across microphone and better ear; and
3. When the better ear was open or closed with earmold impression material and a noise attenuating earmuff, averaged across microphone and loudspeaker array. This experimental condition was included to duplicate the typical clinical measurement of the Baha completed at the initial fitting. Occluding the better ear allows the audiologist to determine how much benefit the patient receives from the Baha alone without help from the better ear.

Any significant two or three factor interactions between the three independent variables were also examined. A secondary goal was to assess perceived subjective benefit between the unaided and aided conditions utilizing the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire (Cox and Alexander, 1995).

METHODS

Subjects

Nineteen subjects were recruited from Washington University's Center for Advanced Medicine and surrounding clinics via either a telephone script or letter approved by the Human Research Protection Office (HRPO) at Washington University. Each subject signed an *Informed Consent Form* approved by HRPO either prior to or at the initial visit. In order to qualify for entrance into the study, each subject was required to (1) be a current user of the Baha; (2) have a USNHL, defined as normal hearing (PTA $\leq$20 dB HL at 500, 1000, 2000, and 3000 Hz) with a word recognition score (WRS) of 90–100% at the most intelligible level (MIL) in the better ear and a profound sensorineural hearing loss and/or poor WRS in the poorer ear; (3) be a native English speaker; and (4) be willing to attend each visit and complete the questionnaire. Subjects were excluded if (1) they did not meet the inclusion criteria described above, (2) were nonambulatory, and (3) had a history of chronic or terminal illness.

Otoscopy, pure-tone air conduction audiometry (at 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz), and WRS testing, utilizing the compact disc recording of the female version of the NU-6 (Tillman and Carhart, 1966) word list at the subject's MIL, were performed to determine if he or 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 subject and asking the subject to indicate when the presentation level was most intelligible and at a comfortably loud level. Three potential subjects could not participate due to poorer hearing thresholds than the inclusion criteria in the better ear, leaving 16 subjects that participated in the study. An a priori power analysis utilizing G*Power 3.0.10 determined that 12 subjects were required to determine statistical significance based on the means (2.0 and -0.3 for OM and DM, respectively) and SDs (2.6 and 2.3 for OM and DM, respectively) reported in a previous study using similar test conditions (Valente et al, 2006), a correlation between means of 0.5, a two-tailed test, alpha of 0.05, and power of 0.80.

Mean hearing thresholds in the better and poorer ear and $\pm$1 SD are reported in Figures 1 and 2, respectively. The mean PTA (at 500, 1000, 2000, and 3000 Hz) for the better ear was 11.0 dB HL (SD = 5.1 dB HL) and 101.6 dB HL (SD = 23.8 dB HL) for the poorer ear. The mean WRS was 97.5% (SD = 2.9%) for the better ear and 23.5% (SD = 9.6%) for the poorer ear. Seven subjects were male and nine were female with a mean age of 52.4 yr (SD = 12.6 yr). Hearing loss etiology in the poorer ear included Ménière's disease (n = 2), acoustic neuroma (n = 7), congenital deafness (n = 2), sudden sensorineural hearing loss (n = 4), and idiopathic (n = 1). Eleven subjects wore the Divino, three the Intenso™, and two the Compact, one of which had the optional DM accessory (DMic) (the interested reader can access www.cochlearamericas.com concerning differences between these Baha models). Subjects'

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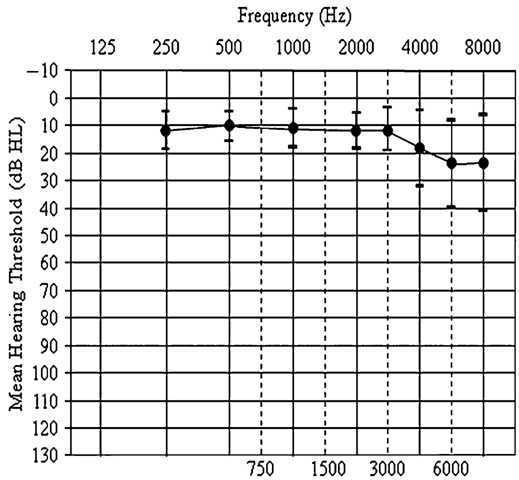

Figure 1. Audiogram reporting the mean (●) and ±1 SD for hearing thresholds in the better ear.

mean years of experience with the Baha was 1.7 yr (SD = 1.8 yr). Eight subjects wore the Baha on the right side, and eight wore the Baha on the left side.

If a subject currently wore the Divino (n = 11) for a minimum of four weeks, all testing occurred at the first visit. If a subject did not currently wear the Divino (n = 5), he or she was fit with a loaner Divino and was allowed four weeks to acclimatize to the Divino before HINT testing. All Divinos, own or loaner, were adjusted with the tone control and automatic gain control output to full on. These settings remained constant throughout the study. The five subjects fit with a loaner Divino returned 1 wk later or were contacted (due to travel limitations) for fine-tuning, if necessary, and to address any concerns. None of the five subjects that returned or called required fine-tuning of the Divino.

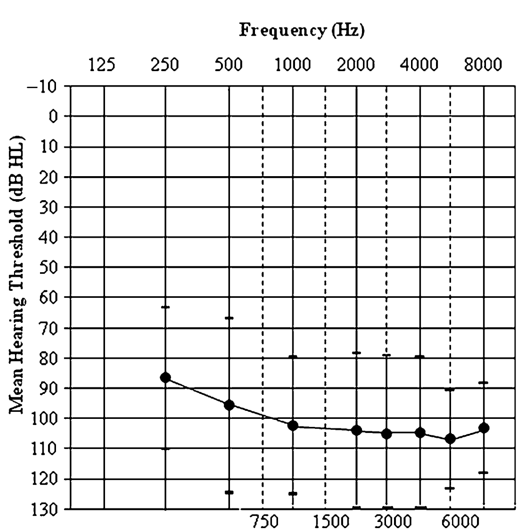

Figure 2. Audiogram reporting the mean (●) and ±1 SD for hearing thresholds in the poorer ear.

Electroacoustic Verification of Microphone Performance

A TU-1000 skull simulator was utilized to perform electroacoustic measures of the output force level (dB SPL) of the Divino's OM and DM between 250 and 8000 Hz. The TU-1000 skull simulator simulates properties of the average mastoid bone and overlying tissues (IEC, 1990). The Divino connects to the TU-1000 skull simulator via an abutment similar to the titanium abutment implanted in the mastoid (see Håkansson and Carlsson, 1989; Stenfelt and Håkansson, 1998 for a more detailed description).

The TU-1000 skull simulator was utilized to verify that the DM was working properly and to quantify the magnitude of the DM's front-to-back ratio (FBR) before HINT testing was performed. Before electroacoustic measures were performed, the Divino was dehumidified and the microphone ports cleaned with a MedRx® Ultra Vac to remove any debris that could deteriorate DM performance. The #13 zinc air battery was verified to ensure the battery was fully charged. The reference microphone of the Audioscan® Verifit® was calibrated according to the Audioscan Verifit user's guide version 3.0 (Audioscan Verifit, 2007). After the Divino was cleaned and dehumidified, the Divino was coupled to the TU-1000 skull simulator connected to the Audioscan Verifit, and the volume control of the Divino was adjusted to full on (volume level of three) for electroacoustic testing.

The Divino was placed in the OM mode via the program switch (up position) to measure OM performance using "dual noise" at 70 dB SPL (Audioscan, 2004). The Divino was then switched to the DM mode (down position) and adjusted to the left or right, depending on the side the Divino was worn, to measure the maximum directional response (i.e., greatest attenuation), and the test was repeated. The DM was working properly when the front measure resulted in greater output force level (dB SPL) than the back measure.

R-Space™ System

The R-Space system consists of eight Boston Acoustics CR-65 loudspeakers (dimensions: 257 × 162 × 200 mm; frequency response (±3 dB): 65–20,000 Hz; crossover frequency: 4200 Hz; woofer: 135 mm copolymer; tweeter: 20 mm dome; nominal impedance: 8 ohms) 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 m^3) 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). Nine discrete audio channels (sentences from 0° and noise from all eight loudspeakers) were delivered from a Macintosh-driven digital audio

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workstation, using MOTU Digital Performer 6 software and a MOTU Model 828 eight-channel FireWire A/D-D/A converter. All loudspeakers were driven by the individual channels of a QSC CX168 eight-channel amplifier.

Before calibration of the loudspeaker array, a QC-20 calibrator was used to check the calibration of a Quest 1900 Precision Sound Level Meter (SLM) with a 1 inch measurement microphone. The calibrator output was measured through the SLM and was determined to be within ±0.1 dB of the targeted 94 dB SPL. Then, to calibrate the loudspeaker system, the measurement microphone was placed at ear level, with the subject absent, at grazing incidence (pointing up), at the center of the loudspeaker array. A prerecorded, "nearly" pink noise signal was presented through each loudspeaker, one at a time, and the gain of the corresponding amplifier channel was adjusted so that the SLM registered 84 dBA ±0.5 dB. Once calibration was ascertained in this way, software attenuators within the digital audio programming provided the necessary attenuations to produce the desired nominal presentation level of 65 dBA, as verified by empirical measurements of Leq (made by R-Space programmer L. Revit, pers. comm.) prior to the beginning of the study.

The eight channels of restaurant noise used as competing noise in this study were recorded simultaneously at Lou Malnati's restaurant in Elk Grove Village, IL, using the patented R-Space recording method. Eight high-order directional microphones were placed pointing outward in a horizontal circular array (one microphone at every interval of 45°), capturing restaurant sounds at points two feet from the center of the microphone array. During playback, the natural signal paths were completed in the laboratory by the array of loudspeakers pointing inward from 2 ft from the center of the array. (See Revit et al, 2007, for a complete description of the R-Space recording and playback methods). As expected in a crowded, partially reverberant restaurant, the eight simultaneous channels of restaurant noise consisted mostly of naturally uncorrelated elements. At times during the restaurant recording when a nearby talker may have been located between the pickup patterns of two adjacent microphones in the recording array, the playback of that talker would be correlated across the corresponding adjacent channels, presented as a "phantom center" image between the corresponding adjacent loudspeakers. Except for such isolated cases of adjacent-channel correlation (reflecting what occurred naturally in the restaurant), the signals in the restaurant simulation were effectively uncorrelated (Compton-Conley et al, 2004). Compton-Conley et al (2004, fig. 4, p. 447) reported that the average long-term speech spectrum of the R-Space restaurant noise was similar to the average long-term speech spectrum of the HINT sentences.

The purpose for using this continuous noise rather than the gated noise provided by the HINT recording was because the noise more closely approximates a "real-world" listening condition. Finally, a lavaliere microphone was placed near the subject's mouth so the examiner could hear the subject's responses to the HINT sentences. The R-Space system was calibrated prior to each test session.

Hearing in Noise Test (HINT)

The HINT consists of 250 sentences (25 lists of 10 sentences per list) read by a male speaker. The first 200 sentences (20 lists) were utilized in this study. The sentences are of approximately equal length (six to eight syllables) and difficulty (first-grade reading level) and have been digitally recorded for standardized presentation. The HINT estimated 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 two lists (10 sentences per list) for each of the eight experimental conditions. The first sentence was presented at +8 dB signal-to-noise ratio (SNR) with the noise fixed at 65 dBA. This presentation level was based on starting levels of three of the 16 subjects that participated in a pilot study. The first sentence was repeated, increasing the level of presentation by 4 dB, until repeated correctly by the subject. Subsequently, the intensity level was decreased by 4 dB and the second sentence was presented. The stimulus level was raised (incorrect response) or lowered (correct response) by 4 dB after the subject's response to the second through fourth sentences. The first four sentences acclimatize subjects to the task and are not included in the calculation of the final RTS. The step size was then reduced and fixed at 2 dB after the fourth sentence, and a simple up-down stepping rule was continued for the remaining 16 sentences. Calculation of the RTS is based on averaging the presentation level of sentences 5 through 20, plus the calculated intensity for a 21st presentation, which is determined by the response for sentence 20. HINT sentence lists were counterbalanced for each subject.

A repeated measures design was utilized in which each subject was tested with each of the three independent variables of microphone, loudspeaker array, and better ear across eight treatment levels (see Figure 3 for a graphical depiction of the eight treatment levels). The Divino was placed in either the OM or DM mode, the better ear was either open or closed, and the volume control was adjusted to full on for the entire test session. The three independent variables of microphone, loudspeaker array, and better ear were counterbalanced for each subject to prevent order effects. The subject was seated in the center of the R-Space system facing the front (0°) loudspeaker, and head placement was

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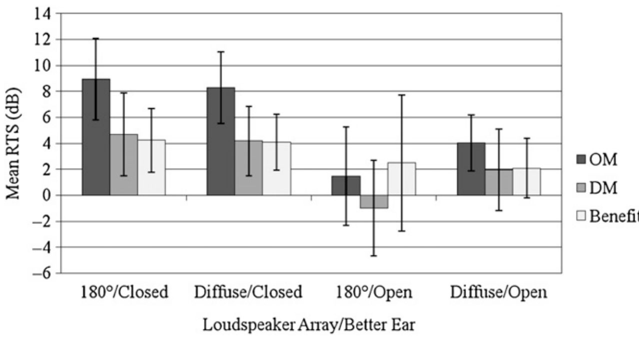

Figure 3. Mean RTS and resulting benefit and ±1 SD for each of the eight experimental conditions. A lower RTS indicates better performance. OM = omnidirectional microphone; DM = directional microphone.

level with the loudspeakers. Each subject was instructed to face the dot in the center of the front loudspeaker throughout the entire test session and told that sentences would be arriving from the front loudspeaker and restaurant noise would be heard from either behind the subject or from all eight of the surrounding loudspeakers. Subjects were asked to repeat the sentence exactly as heard, and if unsure, subjects were instructed to take a guess.

A HINT RTS was obtained for each of the three independent variables of microphone (OM and DM), loudspeaker array (speech from 0° and uncorrelated R-Space restaurant noise from either 180° [behind the subject] or a diffuse field [from each of the eight loudspeakers]), and better ear (open and closed with a silicone earmold impression and covered with Bilsom Thunder T1 earmuffs). It should be noted that two subjects required retesting. Subject 3 was retested due to reaching presentation level limits for the sentences (needed a higher SNR than was available via the software). The equipment software was reprogrammed to allow a higher presentation level for the sentences, and the subject was retested at a second test session. Subject 12 was retested due to unusually large benefit (approximately 13 dB) with the DM for the 180°/ear closed condition. Retest results were similar at the second test session, and, therefore, the most recent test results were utilized. Also, Subject 11 experienced feedback when the volume control was set full on; therefore, the volume control was slowly decreased until feedback was no longer present (volume control at approximately 1.5). The HINT test session was approximately 45 min in length. At the end of the study, subjects were compensated $50 for participation.

Abbreviated Profile of Hearing Aid Benefit (APHAB)

The APHAB is a questionnaire that measures subject's impressions of how well he or she performs in 24 listening environments for four subscales (six listening environments per subscale): Ease of Communication (EC), Background Noise (BN), Reverberation (RV), and Aversiveness (AV). Subjects rate how much difficulty he or she has in each environment on a seven-point assessment scale when unaided and aided. The resulting problem scores are subtracted from each other to determine the amount of benefit the patient perceives from the aided condition compared to unaided. The unaided and aided portions of the APHAB were completed at the last visit. Subjects were allowed to compare responses from the unaided portion with the aided portion. It is important to note that it is unknown whether subjects wore the Divino in the OM only, DM only, or a combination of both and in which environment a specific microphone mode was utilized as the Divino does not have datalogging. These subjective impressions, therefore, cannot be attributed to a specific microphone mode worn in a certain environment.

RESULTS

Objective Results

The mean RTS, benefit, and ±1 SD for each of the eight experimental conditions is reported in Figure 3. An RTS of 0 dB indicates the subject required the level of the sentences to be equal to the level of the noise (65 dBA) to correctly repeat HINT sentences 50% of the time. A higher RTS reflects poorer performance, and a lower RTS reflects better performance. Benefit was calculated by subtracting DM from OM; therefore, positive RTS benefit indicates better performance for the DM. Based on these results, greater benefit was provided by the DM in the 180°/closed ear (directional advantage = 4.2 dB), diffuse/closed ear (directional advantage = 4.1 dB), 180°/open ear (directional advantage = 2.5 dB), and diffuse/open ear (directional advantage = 2.1 dB) conditions.

Main Effects of Microphone, Loudspeaker Array, and Better Ear

The main effects of microphone, loudspeaker array, and better ear mean RTS and ±1 SD averaged over treatment levels is reported in Figure 4. A mean RTS for microphone, averaged across loudspeaker array and better ear, was 5.7 dB (SD = 4.3 dB) and 2.5 dB (SD = 3.9 dB) for OM and DM, respectively, resulting in an overall directional advantage of 3.2 dB. Mean RTS for loudspeaker array, averaged across microphone and better ear, was 4.6 dB (SD = 3.5 dB) and 3.5 dB (SD = 5.0 dB) for diffuse and 180° conditions, respectively, resulting in overall better performance in the 180° loudspeaker array condition by 1.1 dB. A

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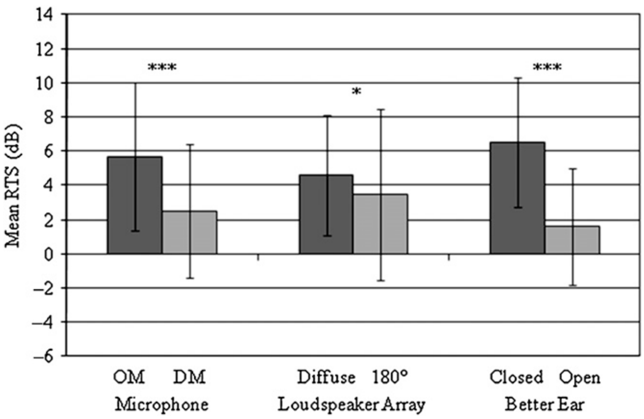

Figure 4. Mean RTS and ±1 SD for the three independent variables of microphone, controlling for loudspeaker array and better ear; loudspeaker array, controlling for microphone and better ear; and better ear, controlling for microphone and loudspeaker array. A lower RTS indicates better performance. *$p < 0.05$, ***$p < 0.001$, OM = omnidirectional microphone, DM = directional microphone.

mean RTS for the better ear, averaged across microphone and loudspeaker array, of 6.5 dB (SD = 3.8 dB) and 1.6 dB (SD = 3.4 dB) was reported for closed and open ear conditions, respectively, resulting in overall better performance with the better ear open by 4.9 dB.

A three-factor repeated measures analysis of variance (ANOVA) was performed to determine if the reported mean differences in RTS across the three independent variables of microphone, loudspeaker array, and better ear were statistically significant. Analysis revealed that mean differences in RTS for microphone (F = 42.43; df = 1,15; $p < 0.001$), loudspeaker array (F = 4.74; df = 1,15; $p = 0.046$), and better ear (F = 123.75; df = 1,15; $p < 0.001$) conditions were statistically significant. Results also revealed statistically significant post hoc interactions between loudspeaker array and better ear (F = 20.76; df = 1,15; $p < 0.001$) and between microphone and better ear conditions (F = 5.11; df = 1,15; $p = 0.039$). All other post hoc interactions were not statistically significant. A summary of mean difference, 95% confidence interval of the mean difference, Cohen's D, and p-value of the statistically significant post hoc interactions is reported in Table 1.

Post-Hoc Interactions

The statistically significant interactions between loudspeaker array by better ear and between microphone by better ear are reported in Figures 5 and 6, respectively. Figure 5 indicates that differences between the open ear and closed ear were greater for the 180° loudspeaker array (mean difference) than for the diffuse loudspeaker array (mean difference) condition. Bonferroni-adjusted pairwise comparisons indicated statistically significant differences between 180° closed and 180° open ($p < 0.001$) and between closed diffuse and open diffuse conditions ($p < 0.001$), with an advantage for the open ear of 6.6 dB and 3.2 dB, respectively. Comparisons within each better ear condition indicated statistically significant differences between open 180° and open diffuse conditions, with an advantage in the 180° condition of 2.8 dB ($p < 0.001$). The difference for closed ear was not statistically significant ($p = 0.38$). Figure 6 reports differences between the OM and DM conditions were greater for the closed ear (mean difference) than for the open ear (mean difference) condition. Bonferroni-corrected pairwise comparisons indicated statistically significant differences between closed OM and closed DM ($p < 0.001$) and between open OM and open DM conditions ($p < 0.001$), with a directional advantage of 4.2 and 2.3 dB, respectively. Likewise, statistically significant differences were reported between OM open and OM closed ($p < 0.001$) and between DM open and DM closed conditions ($p < 0.001$), with an open ear advantage of 5.8 and 4.0 dB, respectively. The differences between the means and the 95% confidence intervals for the differences between the means for the statistically significant post hoc interactions are reported in Figure 7. All 95% confidence intervals for the difference between the means reported in Figure 7 appear to be significant as none of the 95% confidence intervals cross 0.

APHAB

Unaided and aided mean problem and benefit scores and ±1 SD for the APHAB EC, BN, RV, and AV subscales are reported in Figure 8. The results for the AV subscale will not be discussed as this subscale has not been found to be as clinically relevant as the EC, BN, and RV subscale benefit scores (Cox and Alexander, 1995). Mean problem scores for unaided and aided conditions were 28.7% (SD = 13.0%) and 18.2% (SD = 20.6%) for EC, 55.6% (SD = 16.1%) and 30.9% (SD = 13.7%) for BN, and 43.5% (SD = 12.9%) and 29.4% (SD = 12.8%) for RV, respectively. These results indicate less perceived problems for the Divino relative to unaided resulting in mean benefit of 10.6% for EC (SD = 18.4%), 24.8% for BN (SD = 14.8%), and 14.1% (SD = 17.1%) for RV.

A paired samples *t*-test was performed to determine if statistically significant differences in problem scores (benefit) existed between the unaided and aided conditions. Results revealed statistically significant differences between the unaided and aided problem scores for EC (t(15) = 2.29; 95% CI = 0.7–20.4; $p = 0.037$), BN (t(15) = 6.71; 95% CI = 16.9–32.7; $p < 0.001$), and RV (t(15) = 3.31; 95% CI = 5.0–23.2; $p = 0.005$) subscales, with subjects reporting lower problem scores (more benefit) for the Divino relative to unaided on all three subscales. In order for results to be considered clinically significant, a difference of at least 5% must be present

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Table 1. Statistically Significant Post Hoc Interactions

Comparison	Differences between the Means (dB)	95% CI for Differences between the Means	Cohen's D	p-value
Better Ear × Loudspeaker Array				$p < 0.001$
Open Diffuse × Open 180°	2.8	1.46–4.07	1.39	$p < 0.001$
180° Closed × 180° Open	6.6	5.01–8.13	2.43	$p < 0.001$
Diffuse Closed × Diffuse Open	3.2	2.49–3.98	1.93	$p < 0.001$
Better Ear × Microphone				$p = 0.039$
OM Closed × OM Open	5.8	4.29–7.40	2.11	$p < 0.001$
DM Closed × DM Open	4.0	3.00–4.92	1.80	$p < 0.001$
Open OM × Open DM	2.3	1.36–3.21	1.42	$p < 0.001$
Closed OM × Closed DM	4.2	2.45–5.89	1.48	$p < 0.001$

Note: CI = confidence interval; OM = omnidirectional microphone; DM = directional microphone.

on all three subscales of EC, BN, and RV (<11% chance that the observations occurred by chance) (Cox and Alexander, 1995). Results revealed a >10% difference on all three subscales of EC, BN, and RV, indicating a <4% chance that the observations occurred by chance (Cox and Alexander, 1995).

DISCUSSION

Objective DM Performance

The results reported here suggest improved speech recognition in noise for the DM for each of the listening conditions of 180°/open ear, 180°/closed ear, diffuse/open ear, and diffuse/closed ear. The mean directional advantage for 180° was 2.5 and 4.2 dB for open and closed ears, respectively, and 2.1 and 4.1 dB for diffuse with the better ear open and closed, respectively. According to Soli and Nilsson (1994), each 1 dB increase in HINT performance is equal to approximately a 10% increase in sentence recognition in noise. The DM in the Divino, therefore, could provide a mean improvement in sentence recognition in noise of approximately 21–42% compared to OM. The open ear condition, which would be considered the "real-world" condition, provided a 21–25% improvement for speech recognition in noise for the DM compared to OM in the diffuse and 180° loudspeaker arrays, respectively.

Kompis et al (2007) examined DM performance in the Divino for a 180° listening condition and reported a statistically significant directional advantage of 2.3 dB between the Compact OM and Divino DM. This is in agreement with the mean RTS of 2.1 dB for the 180°/open ear condition reported in this study. Kompis et al (2007), however, reported no significant differences (approximately 1 dB) between the Divino's own OM and DM. It should be noted that different speech materials (HINT compared to the Basler sentence test), noise (uncorrelated, R-Space restaurant noise compared to an unspecified noise), noise level (65 dBA compared to 70 dB SPL), scoring (correctly repeated whole sentence versus key words), and type of hearing loss (USNHL compared to bilateral conductive and/or mixed hearing loss) may account for the differences between the two studies.

Results from this study are also in agreement with studies that have examined conventional BTE and

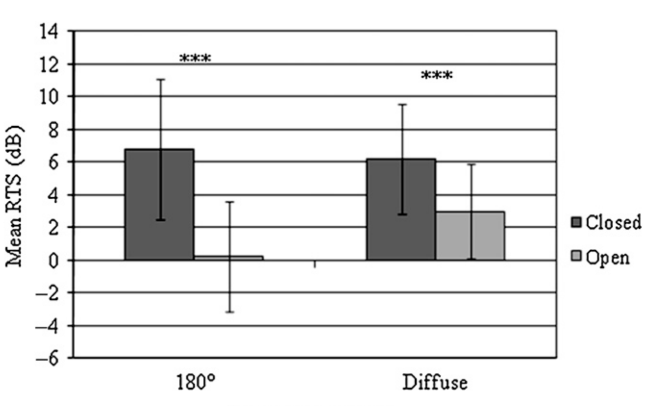

Figure 5. Mean RTS and ±1 SD for the independent variables of loudspeaker array by better ear, controlling for microphone. A lower RTS indicates better performance. ***$p < 0.001$.

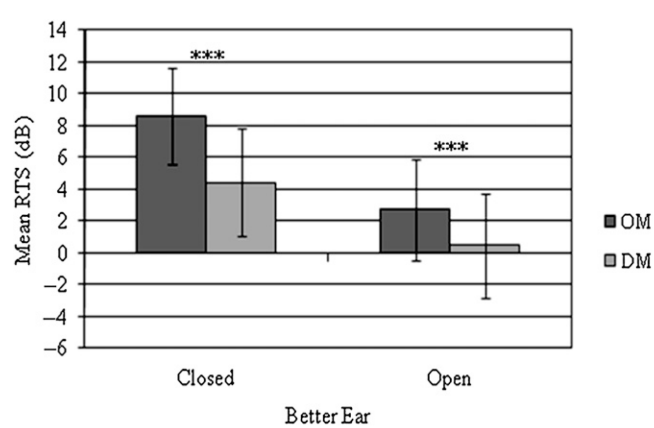

Figure 6. Mean RTS and ±1 SD for the independent variables of better ear by microphone. A lower RTS indicates better performance. ***$p < 0.001$, OM = omnidirectional microphone, DM = directional microphone.

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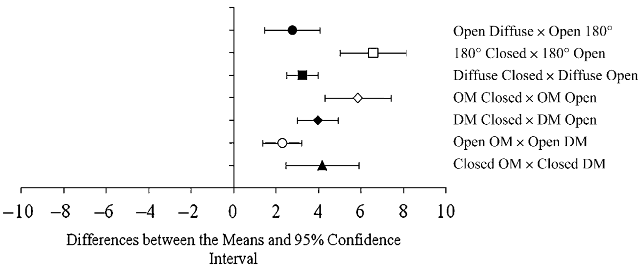

Figure 7. Mean and 95% confidence interval for differences between the means for statistically significant post hoc interactions.

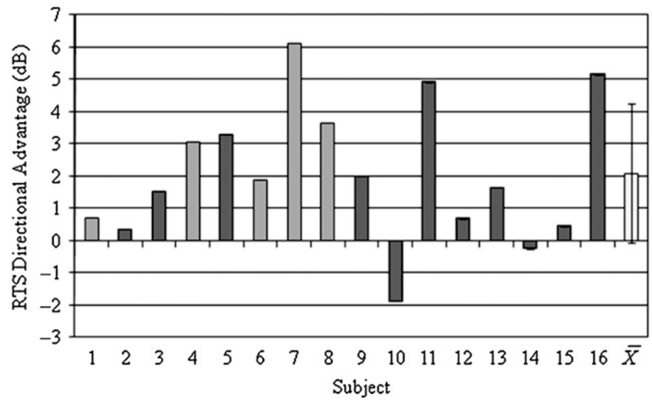

Figure 9. RTS directional advantage for the 16 subjects for the diffuse/open ear listening condition. A positive RTS indicates benefit for the DM. Lighter shaded bars indicate subjects that were fit with a loaner Divino. Mean RTS and ±1 SD for the 16 subjects is displayed in the far right bar.

custom hearing aids. These studies have reported a directional advantage for 180° of 3.2 and 8.6 dB (Valente et al, 1995, 2000) and for diffuse (defined in these studies as speech from 0° and noise from a four loudspeaker array) of 2.7 and 5.8 dB (Pumford et al, 2000; Valente et al, 2000), which are slightly greater than directional advantage for the Divino (2.5 dB for 180°/open and 2.1 dB for diffuse/open). Differences could be due to type of hearing loss examined (bilateral versus unilateral sensorineural), differing polar patterns, and placement of the Baha's microphones compared to BTEs and custom hearing aids.

It is interesting to note that although there was an overall agreement of benefit with the Baha, there was a variable amount of benefit among subjects. RTS directional advantage for each subject for the diffuse/open ear listening condition is reported in Figure 9. A positive RTS indicates better performance for the DM. This listening condition was highlighted as it has the greatest external validity because this environment represents the most typical "real-world" listening condition (speech from the front and noise surrounding the listener with the better ear open). The five subjects provided with loaner Divinos are reported as the lighter shaded bars. Fourteen of the 16 subjects had a directional advantage ranging from 0.4 to 6.1 dB, with two subjects, 10 and 14, performing better with the OM. Intersubject variability for the other listening conditions was similar to this condition. It is interesting to note that subjects that performed better with the OM were different for each condition (no subject performed better with the OM on two or more of the experimental conditions), indicating across all listening conditions, overall, subjects achieved better speech recognition in noise using the DM.

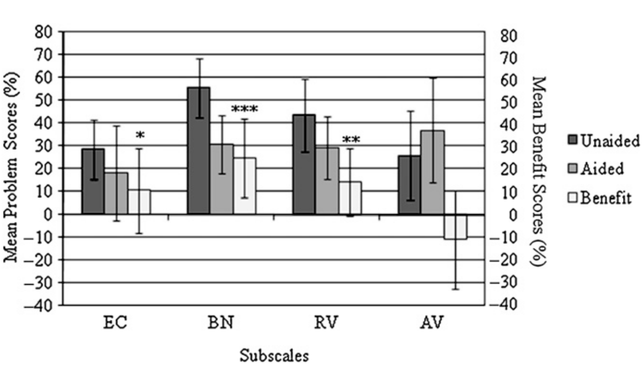

Figure 8. Mean and ±1 SD for problem and benefit scores for the Ease of Communication (EC), Background Noise (BN), Reverberation (RV), and Aversiveness (AV) subscales. A higher problem score indicates poorer perceived performance for the respective subscale. A positive benefit score indicates greater perceived benefit for aided (Divino) relative to unaided. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

There are several factors that could have contributed to the reported intersubject variability. One factor is hearing thresholds in the better ear as ten subjects had thresholds >20 dB HL beyond 3000 Hz. These subjects could have received less high-frequency consonant information, which is important for speech recognition, and, therefore, these subjects could have performed poorer than those with normal thresholds. Subjects also had hearing thresholds between 500 and 3000 Hz from 0 to 20 dB HL as well, with better thresholds potentially providing a lower (better) RTS in noise. A second factor that is related to hearing thresholds is sensation level. Sensation level considers hearing thresholds in the better ear and interaural attenuation, which determines how well the signal is received (attenuated by the skull) in the better cochlea. Higher interaural attenuation and poorer hearing thresholds could result in poorer speech recognition in noise due to decreased audibility of the amplified signal in the better ear.

Cognitive factors such as a subject's ability to focus on the speech signal in noise (auditory figure-ground) and attention may have also contributed to intersubject variability. Testing was not conducted to determine if central deficits existed for subjects that participated in the study; however, a decreased ability to process speech in noise, along with only having a monaural input, could significantly decrease the RTS. Also HINT testing was

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approximately 45 min, which is a long period of time to attend to sentences in a difficult listening environment. The noise, although simulating a "real-world" listening environment, was very distracting as it contained music, conversations, and environmental sounds such as utensils hitting tables and plates breaking. Also, since the level of noise fluctuated, there were acoustic holes where the sentences may have been easier to hear at some points than others. Finally, the test-retest reliability for the HINT sentences utilizing the R-Space restaurant noise in this population is unknown and warrants further investigation.

There are also two additional factors concerning the Divino that may have contributed to the reported intersubject variability. The first factor is the FBR of the DMs. The mean FBR of the 16 Divinos and ±1 SD is reported in Figure 10. There was wide variability in FBR between the Divinos with some DMs providing greater attenuation than others. A decreased FBR from the back and sides could cause poorer speech recognition in noise than having a DM with a better FBR. The second factor is abutment placement. Microphone placement of the Baha, which is dependent on abutment placement, is very different than microphone placement for BTEs and custom hearing aids. Whereas the DM in BTEs are above the pinna and for custom hearing aids in the bowl of the concha, the DM for the Baha is behind the pinna, which could potentially decrease the effectiveness of the DM due to proximity to the pinna. It is unknown how the Baha's proximity to the pinna would affect the OM and DM; however, Ricketts (2000) noted that when DMs in a BTE hearing aid were in close proximity to the pinna a "sound shadow" was created that decreased the directivity index in the high frequencies by approximately 3 dB. Pinna proximity could also potentially decrease DM performance in the Baha. In a study completed by Oeding and Valente (2010), which used some of the subjects participating in this study, it was observed that abutment placement

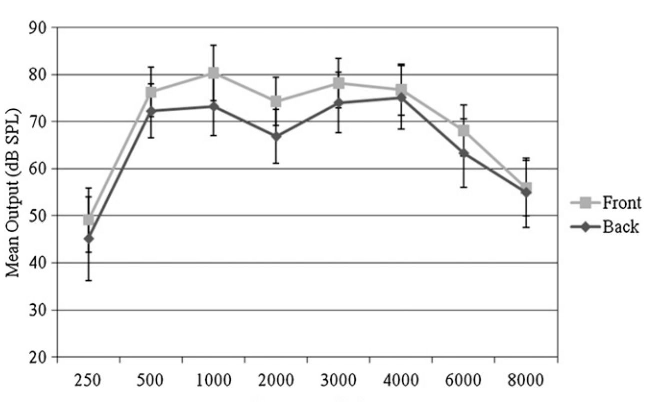

Figure 10. Mean and ±1 SD of the output (dB SPL) for the front-to-back ratio measurements of the 16 Divinos utilized in this study.

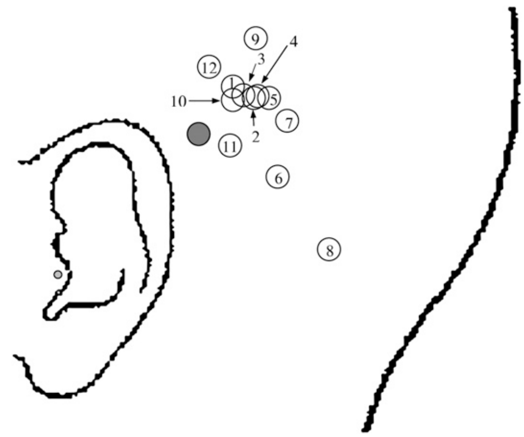

Figure 11. Baha abutment placement of subjects from Oeding and Valente (2010) compared to the suggested abutment placement (gray circle). The dot on the tragus was utilized as a reference point for measuring the different abutment angles (in degrees) and distances (in mm) for each subject. Please note that the distance from the tragus to the abutment in this diagram was drawn to scale. Diagram of ear was taken from http://content.answers.com/main/content/img/oxford/Oxford_Sports/0199210896.Frankfort-plane.1.jpg. Reprinted with permission from *Audiologia Hoy* 7(1):18 (Oeding and Valente, 2010).

was highly variable for the 12 subjects (see Figure 11). The gray dot in Figure 11 represents the suggested abutment placement of 45° and 50–55 mm from the external auditory meatus (Brenner et al, 2007). There is a great amount of intersubject variability for abutment placement, with many of the subject's abutments placed at farther distances and different angles than the suggested abutment placement. Many factors are used to determine abutment placement, such as integrity of the mastoid as well as pinna proximity to the suggested placement (the Baha may be too close to the pinna if the suggested placement is used). Also, varying abutment distances between subjects could cause the Baha to be slightly closer or farther from the sentences and, therefore, cause differences in SNR to the microphone across the 16 Divinos. All these factors warrant further study to determine their impact on speech recognition in noise for persons with USNHL.

APHAB

Results reported statistically and clinically significant benefit scores >10% for the EC, BN, and RV subscales of the APHAB for the Divino relative to unaided. Previous studies examining the APHAB in subjects with USNHL also reported either 5% benefit (OM: Bosman et al, 2003; Niparko et al, 2003; Wazen et al, 2003; Baguley et al, 2006) or 10% benefit scores (OM: Hol et al, 2004; Hol et al, 2005; Newman et al, 2008; Dumper et al, 2009; Yuen et al, 2009; DM: Linstrom et al, 2009) for the Baha on all three subscales. Lin et al (2006) examined the OM and DM as separate aided

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conditions for the Baha Compact. Lin et al (2006) reported that six of fourteen and three of nine subjects had statistically significant scores on the APHAB for the OM and DM relative to unaided, respectively. Overall these results suggest that patients with USNHL and a Baha perceive clinically significant benefit with the Baha, regardless of whether it has an OM or a DM. Anecdotally, all five subjects that were fit with a loaner Divino inquired about exchanging their devices for the Divino at the conclusion of the study due to perceived benefit with the Divino.

It should be noted that one limitation of utilizing subjective measures is recall bias. The range of experience with the Baha across the 16 subjects was from 1 mo to about 6 yr. Those who wore the Baha for many years may have found it more difficult to remember their unaided experience compared to more recently implanted subjects. Also, the five subjects that had worn another Baha model other than the Divino may have compared their experience with this other model with the Divino rather than comparing unaided to the Divino. The authors, however, feel confident that the results are representative of true differences between aided and unaided because the results reported in this study are similar to previous studies.

CONCLUSION

Results reported an overall statistically significant DM advantage of 3.2 dB, controlling for loudspeaker array and better ear, with a directional advantage ranging from 2.1 to 4.2 dB. APHAB results reported statistically and clinically significant subjective benefit for the Divino relative to unaided. It is, therefore, recommended that audiologists select a Baha model that incorporates a DM (for patients with USNHL defined according to the FDA guidelines) to provide improved speech recognition performance in a noisy listening environment.

During this study Cochlear America's BP-100 (replaced Divino) and Oticon Medical's Ponto Pro and Ponto were introduced in the fall of 2009. These devices provide more advanced features than the Divino, including a multichannel automatic adaptive DM and multichannel automatic noise reduction. Future research should examine whether improvement in speech recognition in a diffuse listening environment occurs between these devices. It is also unknown how often subjects utilized the OM and DM in the current study as datalogging was not available in the Divino. Future studies utilizing the BP-100 and Ponto Pro could utilize this feature to determine how often each microphone mode is utilized and in what listening environments. Finally, future research examining the effect of the physical placement of the Baha abutment could help quantify the impact of pinna proximity on the performance of the OM and DM.

Acknowledgments. The authors would like to thank Michael Strube, PhD, professor of psychology at Washington University, for completing the statistical analysis and providing advice on appropriate interpretation of the data; George Cire, AuD, for providing information on the Baha; Larry Revit, MS, for updating the R-Space system used in this study; Jill Firszt, PhD, for serving as a second reader for this manuscript; and colleagues at surrounding clinics for their help with recruiting subjects. Finally, we wish to thank the subjects, many of whom drove many miles to participate in this study. The contents of this article are solely the responsibility of the authors and do not necessarily represent the official view of NCRR or NIH.

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