Impact of a directional microphone on speech recognition in noise in a BICROS hearing aid

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IMPACT OF A DIRECTIONAL MICROPHONE ON SPEECH RECOGNITION IN NOISE IN A BICROS HEARING AID

By

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A Capstone Project
submitted in partial fulfillment of the requirements for the degree of:

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Approved by:
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Abstract: A double blinded investigation of the performance of directional microphone on the receiver side of a BICROS hearing aid.
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Key Words: Bilateral Contralateral Routing of Signals (BICROS); directional microphone (DM); omnidirectional microphone (OM); hearing aid; asymmetric sensorineural hearing loss (ASNHL); Reception Threshold for Sentences (RTS); Hearing In Noise Test (HINT)
Abbreviations: AM = amplitude modulation; ANOVA = analysis of variance; 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; BTE = Behind The Ear; CROS = Contralateral Routing of Signals; CRT = Canal Receiver Technology; DM = directional microphone; EC = Ease of Communication; FBR = front-to-back ratio; FM = frequency modulation; HINT = Hearing in Noise Test; HRPO = Human Research Protection Office; ILD = interaural level difference; ITD = interaural level difference; MIL = Most Intelligible Level; NAL-NL1 = National Acoustic Laboratories’ Nonlinear version 1 prescriptive target; NU-6 = Northwestern University Test Number 6; OM = omnidirectional microphone; PTA = Pure Tone Average; REAG = real-ear aided gain; REIG = real-ear insertion gain; RTS = Reception Threshold for Sentences; RV = Reverberation; SD = standard deviation; SLM = sound level meter; SNR = signal-to-noise ratio; SPIN = Speech In Noise Test; SRT = Speech Recognition Threshold; WIN = Words In Noise test; WRS = word recognition score
INTRODUCTION

Asymmetric sensorineural hearing loss (ASNHL) defined as unaidable hearing loss in one ear and aidable hearing loss in the opposite ear, presents a unique challenge to patients due to the loss of the benefits of binaural hearing. Studies as early as the 1950’s have described the advantages of binaural hearing including binaural summation and a central release from masking termed “binaural squelch,” improved localization abilities, and improved perceived spatial balance (Bergman, 1957; Dirks and Wilson, 1969; Bess and Tharpe, 1986). Gulick et al (1989) described binaural summation as an advantage in information processing that results in a lower detection threshold with binaural compared to monaural thresholds. This binaural advantage has been reported to be approximately 2-3 dB when listening to soft/near threshold sounds and 6-10 dB for suprathreshold sounds (Bess and Tharpe, 1986). Binaural release from masking or “binaural squelch” is responsible for the “cocktail party effect” (Cherry, 1953; Bronkhorst, 2000). The “cocktail party effect” is the ability of a person to hear a single person in an environment with competing background noise. Interaural differences in the time and intensity of the desired speech signal and the background noise results in a release from the masking noise, which allows the listener to detect the desired speech signal separate from the background noise (Dirks and Wilson, 1969; Flynn et al, 2010).

There are two primary cues that make it possible to detect speech in background noise. These cues are interaural level differences (ILDs) that arise from the head-shadow effect and interaural timing differences (ITDs) between signals reaching the ears of the listener. ITD and ILD cues also aid in the ability of an individual to localize sound. Ones’ ability to localize sound occurs when a sound is perceived as louder at one ear or arrives first at one ear (ILD) compared to the other (ITD). These cues are frequency dependent (Shaw, 1974). High frequency sounds
are localized via ILD cues while low frequency signals are localized utilizing ITD cues because of the head shadow effect. Tillman et al, (1963) first described the head shadow effect for speech and reported that because speech has to travel around the head to reach the opposite ear, the intensity is attenuated by an average of 6.4 dB. Marksides (1977) reported the level of attenuation in the head shadow effect to be frequency dependent. Lower frequency sounds have a longer wavelength and tend to “bend” around the head hence the use of ITD, while higher frequency sounds do not, due to the shorter wavelength of the sound, hence why the use of ILD cues for high frequency sounds.

Individuals with ASNHL lose the advantages of binaural hearing such as binaural summation of loudness and binaural squelch, as well as the ability to localize sounds due to monaural hearing. Several studies have demonstrated that individuals with ASNHL have poorer speech understanding in quiet (Giolas and Wark, 1967) as well as in background noise compared to individuals with either bilateral hearing loss or normal hearing (e.g., Harford and Barry, 1965; Giolas and Wark, 1967). To help alleviate some of the negative effects of ASNHL, an amplification strategy of re-routing the signal from the poorer ear to the better ear via a transmitter (microphone) and receiver (amplifier and/or microphone) was first introduced by Fowler (1960) and was later developed by Harford and Barry (1965). These hearing aids were called Contralateral Routing Of Signals (CROS) and Bilateral Contralateral Routing Of Signals (BICROS) hearing aids and their primary purpose was to eliminate the head shadow effect. BICROS amplification consists of a transmitter (microphone) that is placed on the poorer ear side and transmits sounds arriving at the poorer ear to a receiver (microphone and amplifier) on the better ear, which provides amplification to the sounds on the better ear (Pumford, 2005). The transmitter is placed on the poorer hearing ear and consists of an omnidirectional microphone
(OM) and an FM transmitter that sends the signal to the receiver. The receiver is placed on the better hearing ear and consists of a microphone (possibly a directional microphone [DM]), receiver, and an amplifier that amplifies sound from the poorer and better ear. Early models utilized a hardwire connection between the transmitter and the receiver to transfer the sound from the poorer ear to the better ear. In recent years, however, advancements in amplitude modulation (AM) and frequency modulation (FM) technology have allowed for wireless connectivity between the transmitter and receiver. While BICROS hearing aids do not restore binaural hearing, they do provide a pseudo “two-sided hearing environment,” and help to eliminate the head shadow effect for sounds arriving from the poorer side. The intensity difference and time delay provided from the transmission can also result in a “pseudo head-shadow” effect (Ericson et al, 1988; Taylor, 2010). While Hol et al (2010) demonstrated the use of temporal cues to aid in sound localization by BICROS users, however, the majority of studies do not report localization abilities greater than chance for ASNHL participants.

Recent advances in BICROS hearing aids have resulted in the introduction of two devices: the Unitron Tandem BICROS (4 and 16), and the Phonak CROS/BICROS. These BICROS hearing aids have attempted to improve the users comfort and performance in background noise by incorporating features such as noise reduction algorithms on the receiver and transmitter sides (Unitron Tandem 4 and 16) and an automatic, adaptive multi-channel directional microphone on the receiver side while the transmitter is active (Phonak BICROS). There is very little research, however, examining whether these features improve comfort and/or speech recognition in noise. Del Dot et al (1992) investigated significant differences in the Speech Recognition Threshold (SRT) of BICROS users with the transmitter turned on or off while randomized sentence lists from the Speech Perception in Noise (SPIN) Test were
presented from 0° azimuth and four-talker babble at 40 and 60 dB SPL was presented from 135° and 225°. Results revealed a mean improvement in SRT with the transmitter active compared to the transmitter being inactive of 4.3 dB (p < 0.01) with a 40 dB SPL noise level and 3.4 dB (p < 0.001) with a 60 dB SPL noise level. This indicates the possible benefits of using a BICROS transmitter when noise arrives from behind and speech arrives from the front. One study (Oeding and Valente, 2013) investigated the impact of noise reduction on the transmitter and receiver sides of the Unitron Tandem 16 BICROS on speech recognition in noise and subjective performance. Hearing In Noise Test (HINT) sentences were presented from 0° azimuth and Lou Malnati’s uncorrelated restaurant noise was presented from an eight loudspeaker array (R-SPACE™) including the front loudspeaker. Subjective preferences were measured using the Abbreviated Profile of Hearing Aid Benefit (APHAB) (Cox and Alexander 1995). Results revealed no significant differences in Reception Threshold for Sentences (RTS) between unaided RTS and the three aided conditions (no noise reduction, minimum noise reduction, and maximum noise reduction). Statistically and clinically significant perceived benefit was reported on the APHAB for unaided compared to aided experiences. Oeding and Valente (2013) reported participants’ perceived improved mean benefit with the Tandem 16 BICROS for the EC (Mean = 30.9%; SD = 21.5%), RV (Mean = 40.7%; SD = 21.8%), and BN (Mean = 32.4%; SD = 24.6%) subscales.

Another study examined the automatic, adaptive, multi-channel DM in the Phonak BICROS hearing aid (Williams et al, 2012). Speech recognition in noise was assessed using the Words In Noise (WIN) test presented in the soundfield at 70 dB SPL. Speech was presented from 0° and noise from 180°, speech was also tested from 90° and 270° with the noise coming from the opposite side as the speech. The participants were tested with their own BICROS
hearing aid and with the Phonak BICROS hearing aid. Results revealed no significant difference between the participants’ own BICROS and the Phonak BICROS (p > 0.05).

It was the unexpected results from Williams et al (2012) that led to the current study. In previous studies examining conventional hearing aids, DM features have shown significant improvement in the presence of background noise compared to OM performance in speech testing (Valente et al 1995, Pumford et al 2000, Amlani A. 2001). In contrast Williams et al (2012) reported no significant improvement with DM active on a Phonak BICROS compared to OM performance. The intention of the current study is to further investigate the active DM features on the Phonak BICROS and compare objective performance across unaided, OM, and DM listening conditions.

The goal of the present study was to evaluate:

1) Whether significant differences exist in the RTS (in dB), for HINT sentences (Nilsson et al, 1994) presented in a diffuse listening environment between unaided, OM, and DM on the receiver side and OM on the transmitter side in the Phonak BICROS hearing aid. The null hypothesis is that there will be no significant differences between unaided, OM, and DM.

2) Whether significant differences exist between unaided and aided problem scores or between the OM and DM problem scores on the Ease of Communication (EC), Background Noise (BN), and Reverberation (RV) subscales of the APHAB questionnaire (Cox and Alexander, 1995). The null hypothesis is that there will be no significant differences between unaided, OM, and DM.

METHODS
Experimental Hearing Aid: Phonak Ambra microP® Hearing Aid and CROS® H2O Transmitter

The Phonak Ambra microP hearing aid (receiver) is a behind-the-ear (BTE) hearing aid that is the highest level of technology in the Spice Core family of hearing aids from Phonak. The hearing aid has 20 bands and channels, an integrated volume control, program button, uses a size 13 battery, can be fit a mild to profound hearing loss, as well as DM and OM features such as “UltraZoom” and “Real-Ear Sound”. UltraZoom is a multi-channel, automatic, adaptive directional microphone setting and “Real-Ear Sound” is a processing algorithm that is designed to provide gain to mimic the natural resonance of the pinna. This processing algorithm accounts for the microphone being placed atop of the pinna when wearing the BICROS as opposed to in the ear canal. The Ambra microP can be paired with the CROS H2O wireless transmitter to create a BICROS hearing aid. The CROS H2O wireless transmitter is equipped with traditional OM capabilities and with Real-Ear Sound. Unlike previous BICROS hearing aids the Phonak BICROS allows the automatic, adaptive multi-channel DM to be activated while the CROS transmitter is activated.

Participants

Twenty-two participants were recruited from the Washington University in St. Louis School of Medicine’s Center for Advanced Medicine either in person or with a telephone script or letter approved by the Human Research Protection Office (HRPO) at Washington University in St. Louis. Each participant signed an Informed Consent document approved by HRPO at the beginning of the initial visit. In order to qualify for the study, each participant was required to: 1) be a current or previous user of a BICROS hearing aid for a minimum of four weeks; 2) have an ASNHL, defined as an aidable hearing loss in the better ear that is appropriate for the Phonak
Ambra microP fitting range, with a word recognition score (WRS) of 60–100% 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. Participants were excluded if: 1) they did not meet the inclusion criteria described above, 2) were non-ambulatory, and 3) had a history of chronic or terminal illness.

Three participants were excluded from the study as one participant had poorer hearing thresholds than the inclusion criteria in the better ear, one participant had better hearing thresholds than the inclusion criteria in the poorer ear, and one participant withdrew after one week of participation due to the inability to adapt to the sound quality of the Phonak BICROS compared to his/her own BICROS. Nineteen participants, therefore completed the study. An a priori power analysis utilizing G*Power 3.0.10 determined that nine participants were required to determine statistical significance based on the means (2.0 and −0.3 for OM and DM, respectively) and standard deviations (SD) (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. Initially the recruitment goal of the current study was 25 participants due to the uncertainty of the means and SDs of Valente et al (2006). After the final data of 15 participants was analyzed, however, it was determined that no more subjects were needed and enrollment ended with 19 participants.

Mean hearing thresholds in the better and poorer ear and ± one SD are reported in Figure 1. The mean pure-tone average (PTA) (at 500, 1000, and 2000 Hz) for the better ear was 30.8 dB HL (SD = 14.2 dB HL) and 78.3 dB HL (SD = 18.1 dB HL) for the poorer ear. The mean WRS was 86.0% (SD = 13.0%) for the better ear and 7.0% (SD = 11.0%) for the poorer ear. Twelve
participants were male and seven were female with a mean age of 73.2 yrs (SD = 8.3 yrs).

Hearing loss etiology in the poorer ear included acoustic neuroma (n = 7), Meniere’s Disease (n = 3), idiopathic sudden sensorineural hearing loss (n = 4), noise induced hearing loss (n = 1), otosclerosis (n = 1), idiopathic etiology (n = 2), and congenital hearing loss (n = 1). Figure 2 reports current amplification used and years of BICROS experience for each of the 19 participants. Two participants were not currently wearing a BICROS at the time of their recruitment; however, both participants had previously worn a BICROS. One participant had worn a BICROS for 6.0 years and the other had worn a BICROS for 7.2 years. Participants’ mean years of BICROS experience was 7.1 yrs (SD = 6.2 yrs). Nine participants wore a right BICROS and ten participants wore a left BICROS.

Pre-Testing

Prior to the initial visit, the Phonak Ambra microP hearing aids (receiver) and CROS H₂O transmitters were paired via manufacturer software (Phonak Target™ 2.0) and performance was verified utilizing a Frye® Fonix® 6500 Hearing Aid Test System and Audioscan® Verifit®. The Frye Fonix 6500 was used to verify the Phonak Ambra hearing aid’s full-on gain test settings via ANSI S.3.22-1996 (1996) (see Figure 3). The performance of the transmitter was verified by coupling the receiver to an HA-2 coupler connected to the test box microphone and placing the receiver on top of the Frye Fonix 6500 test box. The resulting output measures of the receiver set to Full on Gain can be seen at the bottom of Figure 3. Next, the transmitter was placed in the test box in the center of the calibrated test point. A 70 dB SPL speech-weighted composite signal was presented with the test box closed and the resulting measure from the transmitter was obtained (see Figure 4). The Audioscan Verifit system was utilized to verify the performance of the DM on the receiver (see Figure 5). This measure was completed by
performing the Directionality Test in the test box utilizing a 55 dB SPL dual-noise signal that was presented from the right and left loudspeakers. The front and back microphones of the receiver were aligned in the horizontal plane and a printout of the resulting front-to-back ratio (FBR) curve was obtained and recorded for data analysis. Figure 5 reports this FBR response the difference between the two output curves indicates a greater emphasis being placed on sounds from in front of the receiver and a reduction or decreased emphasis on sounds from the rear. This indicates proper DM function for the receiver. All devices performed within the manufacturers’ specifications with the exception of one pair which was unable to be removed from test mode in the manufacturer’s programming software. This pair was returned to the manufacturer and replaced with a new pair that performed within the manufacturers’ specifications.

At the initial visit, otoscopy, pure-tone air conduction thresholds (250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz), pure-tone bone conduction thresholds (at 250, 500, 1000, 2000, 3000 and 4000 Hz), and WRS testing utilizing a compact disc recording of the female version of the Northwestern Auditory Test Number 6 (NU-6) (Tillman and Carhart, 1966) word list at the participant’s MIL, were performed to determine if each participant 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 comfortable loudness level. If the participant met the candidacy requirements, audiometric testing was followed by the fitting of the BICROS device.

Prior to the fitting, the BICROS was preprogrammed with two programs. These programs used the manufacturers’ “speech in noise” program, with acclimatization set to 100%,
using, the National Acoustic Laboratories’ – Nonlinear version 1 prescriptive target (NAL-NL1; Byrne et al, 2001) fitting formula. SoundFlow, the automatic program, was removed so it could not be accessed by participants and NoiseBlock, WindBlock, EchoBlock, SoundRelax, SoundRecover, and the start-up melody were deactivated. The volume control was limited to a 6 dB range for increasing and decreasing the volume. Datalogging was enabled to accurately track hours of use and program use information. WhistleBlock was activated for both programs after a feedback test was performed. The only difference between the two programs was the microphone mode of the receiver. In one program, the receiver side was programmed to “UltraZoom & SNR Boost” (DM for the current study) and in the other program the receiver side was programmed to “Real-Ear Sound” (OM for the current study). The microphone on the transmitter side was set to “Real-Ear Sound” in both programs. These settings remained constant throughout the study.

**Fitting Protocol**

The BICROS hearing aid was fit utilizing real-ear probe microphone measures to ensure each device was fit according to the NAL-NL1 prescriptive target. The NAL-NL1 target was corrected for channel summation (correction set to 18+ channels) via the Frye Fonix 8000 Hearing Aid Analyzer. The corrected target values obtained from the Frye Fonix 8000 were then manually entered into the Frye Fonix 6500 real-ear measurement system. First, the loudspeaker from the real-ear system was positioned at 0° and 12 inches in front of the participant with the reference and probe microphones activated and placed on top of (reference) and in (probe microphone) the better ear. Then the receiver side was fit using real-ear insertion gain (REIG) measures with the NAL-NL1 prescriptive target utilizing the Frye Fonix 6500 Hearing Aid Analyzer with a 50, 65, and 80 dB SPL speech-weighted composite signal. The goal REIG was
measured to be within 5 dB from 500 to 8000 Hz for an input level of 65 dB SPL. The mean NAL-NL1 prescriptive target, mean measured REIG, and the mean difference between each is reported in Figure 6 ± one SD. Then the loudspeaker was positioned at 90° to the poorer ear side and the reference microphone was moved to the poorer ear side. The real-ear aided gain (REAG) was measured by presenting a 65 dB SPL speech-weighted composite signal to the transmitter side and the probe microphone measured the output on the receiver side. Then, the same 65 dB SPL speech-weighted composite signal was presented to the receiver side with the reference microphone on the receiver side and the resulting REAG output measurements were compared to each other to ensure transparency of the signal and to show the transmitter was overcoming the head shadow effect. Figure 7 illustrates this by reporting gain measures for the receiver to be essentially superimposed upon the gain measures of the transmitter. This verification procedure is described further by Pumford (2005) and is used to ensure the elimination of the head shadow effect.

Loudness judgments were performed with each participant by presenting a 50, 65 and 80 dB SPL speech-weighted composite signal from the loudspeaker and the subjective response of the participant was recorded in accordance with Pascoe (1988). These subjective responses were recorded with the goal of soft (50 dB SPL) sounds being perceived as soft, average (65 dB SPL) sounds being perceived as comfortable, and loud (80 dB SPL) sounds being perceived as “loud but okay”. The gain in the two programs were matched (the OM gain was matched to the DM gain settings) for the OM and DM programs. The participants and primary author were blinded to the program order. All programs were accessible via a program button on the receiver. The second author created a randomization chart and placed the programs in a randomized order into the hearing aid after real-ear measures. An electroacoustic analysis of user settings in the first
program was obtained to use as a reference of receiver performance. A program directory was provided to each participant with instructions to set the BICROS to the specified program for the corresponding day of use and to leave the device in that program for the duration of the day. The program directory alternated between program one and program two every other day and two different directories were created to counterbalance the order of the starting program. The program directory was created to ensure equal wear time and acclimatization for each program. The participant was counseled on the various indicator tones present in the BICROS, as well as general care and maintenance.

All participants were contacted via a telephone call one week after the initial visit to address any concerns and to schedule a fine-tuning appointment, if needed. Participants that needed fine-tuning returned one week after the initial visit. In total five of 19 participants returned for fine-tuning. Two of these participants requested the gain on the device be decreased, while two requested the gain be increased, and one needed reinstruction on how to use and care for the BICROS. REIG measures were performed using a 65 dB SPL speech-weighted composite noise after programming adjustments to ensure adequate audibility and that REIG was within the fitting protocol. Datalogging was examined to assess program use and to help ensure equal acclimatization time for each program. Electroacoustic analysis measures at user settings were also performed.

All participants were allowed four weeks to acclimatize to the BICROS before HINT testing. If the participant did not request fine-tuning, the final visit occurred four weeks after fitting of the BICROS device. If the participant did request fine-tuning the final visit occurred four weeks after the second visit. At the final visit, participants completed HINT testing in the
R-SPACE™ System

The R-SPACE system (Figure 8) consists of eight Boston Acoustics CR-65 loudspeakers (dimensions: 257 × 162 × 200 mm; frequency response (± 3 dB): 65–20000 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 m³) with a reported reverberation time of 0.19 sec (Industrial Acoustics Company, personal communication in Oeding K, Valente M, Kerckhoff J, 2010). The circle radius was the depth of the loudspeaker (200 mm) plus two feet. Nine discrete audio channels were utilized in this study (sentences from 0° and noise from all eight loudspeakers) and were delivered from a Macintosh-driven digital audio workstation, using MOTU Digital Performer 6 software and a MOTU Model 828 eight channel FireWire A/D D/A converter. All of the loudspeakers in the array 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 verify the calibration of a Quest 1900 Precision sound level meter (SLM) with a one inch pressure 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 pressure microphone was placed at ear level, with the participant 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 a measurement of 84 dBA ± 0.2 dB was measured with the SLM. This calibration method was repeated prior to the testing of each participant.

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, personal communication in Oeding K, Valente M, Kerckhoff J, 2010). prior to the beginning of a previous study. The eight channels of restaurant noise used for competing noise in this study were recorded simultaneously in Elk Grove Village, IL, at Lou Malnati’s restaurant, 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 two feet from the center of the array. For a complete description of the R-SPACE recording and playback methods, see Revit et al (2007). As one would expect from this type of environment, the eight simultaneous channels of restaurant noise mostly consisted of uncorrelated elements.

There are various times in the restaurant recording when a nearby talker was located between two adjacent microphones in the recording array. The playback of that particular talker would be correlated across the corresponding adjacent channels and be presented as a “phantom center” image between the adjacent corresponding loudspeakers. With the exception of 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 the average long-term speech spectrum of the R-SPACE restaurant noise was similar to the HINT sentences average long-term speech spectrum. This continuous noise rather than the gated noise provided by the HINT recording was utilized to better simulate a “real-world” listening environment. Finally, a lavaliere microphone was placed near the mouth of the participant so the examiner could hear the participant’s responses to the HINT sentences.

**Hearing in Noise Test (HINT)**

The HINT consists of a male talker recording of 250 sentences (25 lists of 10 sentences per list). Of these sentences, the first 240 sentences (24 lists) were utilized in this study. These sentences are nearly equal in length (approximately six to eight syllables) and in the level of difficulty (first-grade reading level). The sentences have been digitally recorded for standardized presentation. The HINT estimated the participants’ RTS (measured in dB) at which sentences, embedded in a recording of uncorrelated restaurant noise, could be repeated correctly 50% of the time. Administration of the HINT required presentation of four lists (10 sentences per list) for each of the three experimental conditions. The first sentence was presented at 0 dB SNR with the noise fixed at 65 dBA. If the participant incorrectly repeated the first sentence, the stimulus presentation level was increased in 4 dB steps, until repeated correctly by the participant. Once the first sentence was repeated correctly the intensity level was decreased by 4 dB and the second sentence was presented. The stimulus level was increased with each incorrect response or decreased with each correct response by 4 dB after the participant’s response to the second through fourth sentences. The first four sentences were used to acclimatize participants to the task and were not included in the final calculation of the RTS. The step size was then fixed at +/- 2 dB (dependent on a positive or negative participant response) after the fourth sentence, and a
simple up-down stepping rule was continued for the remaining 16 sentences. Calculation of the RTS for each pair of sentence lists is based on averaging the presentation level of sentences 5 through 20 and the calculated intensity of a 21st presentation, which is determined by the response for sentence 20. HINT sentence lists were randomized for each participant.

A repeated measures design was utilized in which each participant was tested in both microphone conditions (OM and DM) as well as an unaided condition. Prior to testing, the BICROS was dehumidified and the microphone ports were cleaned with a MedRx® Ultra Vac to remove any debris that could deteriorate DM performance. New #13 zinc air batteries were placed in the BICROS to ensure the battery was fully charged. The BICROS was placed in program one with the volume control at its default setting for electroacoustic analysis of the user settings to ensure optimum performance of the device. Electroacoustic analysis was performed utilizing ANSI standard S.3.22-1996 (1996) and measuring at user settings and the results were compared to the user settings measurements taken at the initial or second visit. The order of the testing conditions was randomized between all participants in order to prevent user and/or tester bias and the participants and primary author remained blinded to the identity of each program until the end of the study. The BICROS was placed in the respective program with the volume control at its default setting or the participant was tested unaided. The participant was seated at the center of the R-SPACE system facing the front loudspeaker at 0° azimuth with their head level with the loudspeakers. Each participant was instructed to face the dot in the center of the front loudspeaker throughout the entire test session. Participants were informed that sentences would be arriving from the front loudspeaker and uncorrelated restaurant noise would arrive from all eight of the surrounding loudspeakers at a level of 65 dB SPL. Participants were asked to repeat the sentence exactly as heard, and if unsure, participants were instructed to take a guess.
A HINT RTS (in dB) was obtained for each of the three test conditions (unaided, OM, and DM). The data obtained from the tests performed was recorded and placed in a Microsoft Excel spreadsheet for statistical analysis. The final test session was approximately one and a half hours in length. At the end of the study, participants were compensated with a box of hearing aid batteries or the option to purchase the BICROS at a reduced cost.

**Abbreviated Profile of Hearing Aid Benefit (APHAB)**

The APHAB is a questionnaire measuring the participant’s impressions of how well he or she performs in 24 listening environments which are divided into four subscales (six listening environments per subscale): EC, BN, RV, and Aversiveness of sounds (AV). The results on the AV subscale were not included in the results section of this study. AV was not included because this subscale has been reported to not be as clinically relevant as the EC, RV, and BN subscales (Cox and Alexander, 1995). Participants were instructed to rate the level of difficulty he or she experiences in each of the independent environments on a seven-point assessment scale comparing unaided and aided conditions and comparing program one and program two (OM compared to DM). The problem scores from the questionnaire are then subtracted from each other to determine the amount of benefit the patient perceives from the aided condition compared to the unaided condition or between the two aided conditions. The APHAB was completed at the last visit and participants were allowed to compare responses for each condition.

**Electroacoustic Verification of Microphone Performance**

The Frye Fonix 8000 Hearing Aid Test System was utilized to verify that the DM on the receiver was working properly, to generate a polar plot of the microphone performance, and to quantify the magnitude of the DM’s FBR after HINT testing was performed. Electroacoustic verification was performed after HINT testing to maintain the blinding of the tester to control for
possible tester bias. The receiver was coupled to the HA-2 coupler and placed into Program One with the volume control in the default position. Measurements were taken in five degree increments utilizing an interrupted composite signal presented at 60 dB SPL at eleven (500, 600, 800, 1000, 1200, 1600, 2000, 2500, 3200, 4000, and 5000 Hz) distinct frequencies. Once the polar plot response was obtained, the receiver was placed into Program Two with the volume control remaining in the default position and the polar plot response was measured. All receiver OM and DM programs were deemed to be operating properly.

RESULTS

Hearing in Noise Test (HINT)

The mean RTS (dB) and ± one SD for each listening condition (unaided, OM, and DM) is reported in Figure 9. A higher RTS indicates poorer performance as the participant requires a higher SNR to repeat the sentences correctly 50% of the time. Minimal differences in mean RTS were noted between the three listening conditions with a mean RTS of 7.3 dB (SD = 4.6 dB) for the unaided condition, a mean of 7.5 dB (SD = 3.3 dB) for the OM condition, and a mean of 6.6 dB (SD = 3.1 dB) for the DM condition.

It is important to note that one participant was unable to complete unaided HINT testing at the final visit of the study due to distress and difficulty of the listening condition and decided to withdraw from this part of the final test condition. This section of the testing was the only section that was not completed by the participant.

A one-way repeated measures analysis of variance (ANOVA) was completed to determine if significant differences were present between the three listening conditions. Results revealed no significant differences between unaided, OM, and DM (F(2,34) = 1.46, p = .246). Therefore, the null hypothesis was accepted.
Abbreviated Profile of Hearing Aid Benefit (APHAB)

OM Compared to DM:

The mean OM and DM Phonak BICROS problem scores, the resulting benefit scores, and ± one SD are reported in Figure 10 for the EC, RV, and BN 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, RV, and BN subscales (Cox and Alexander, 1995). A repeated measures ANOVA was performed for each subscale comparing OM and DM problem scores. Results revealed no significant differences between OM and DM problem scores for the EC (F(1,17) = 0.15, p = 0.70), RV (F(1,17) = 0.09, p = .78), and BN (F(1,17) = 0.55, p = 0.47) subscales. Participants perceived no significant improved mean benefit with the OM compared to DM for the EC (Mean = -0.3%; SD = 3.6%), RV (Mean = -0.3%; SD = 4.7%), and BN (Mean = -0.9%; SD = 5.5%) subscales. Therefore, the null hypothesis stated previously was accepted stating that significant differences did not exist between OM and DM problem scores on the EC, RV, and BN subscales.

Unaided Compared to Aided Condition:

The mean unaided and aided Phonak BICROS problem scores, the resulting benefit scores, and ± one SD are reported in Figure 11 for the EC, RV, and BN subscales. A repeated measures ANOVA was performed for each subscale comparing unaided and aided problem scores. Results revealed significant differences between unaided and aided problem scores for the EC (F(1,18) = 38.21, p < 0.001), RV (F(1,18) = 55.48, p < 0.001), and BN (F(1,18) = 50.87, p < 0.001) subscales. Participants’ perceived improved mean benefit with the BICROS for the EC was 25.9% (SD = 18.3%), for the RV was 34.1% (SD = 20.0%), and for the BN was 27.6% (SD = 16.9%). 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, RV, and BN subscales of the APHAB was accepted. According to Cox and Alexander (1995), the benefit scores were not found to be clinically significant for a 90% critical difference.

Microphone polar plots were performed for OM (see Figure 12) and DM (see Figure 13) to verify DM performance of each participants’ settings. The mean 2D-DI value for OM performance was 1.8 dB (SD = 0.8 dB), and the mean 2D-DI value for DM performance was 5.6 dB (SD = 1.5) when measured from 500 Hz to 5000 Hz (see Figure 14).

A Pearson correlation analysis was performed on mean unaided, OM, and DM HINT RTS compared to PTA and WRS. A positive correlation of 0.802 was found between PTA and unaided HINT RTS values (Figure 15). This indicates that with the current sample size it is possible to detect a positive correlation to a 0.802 magnitude. A positive correlation of 0.609 was found between PTA and DM HINT RTS values (Figure 16). This indicates that with the current sample size it is possible to detect a positive correlation to a 0.609 magnitude. A positive correlation of 0.641 was reported between PTA and OM HINT RTS values (Figure 17). This indicates that with the current sample size it is possible to detect a positive correlation to a 0.641 magnitude. A negative correlation value of -0.861 was reported to exist between PTA and WRS. This indicates that the lower (better) a participant’s PTA, the higher (better) a participant’s WRS will be. A negative correlation value of -0.789 was reported to exist between WRS and unaided HINT RTS (Figure 18), while a negative correlation value of -0.695 was reported to exist between WRS and OM HINT RTS (Figure 19), and a negative correlation value of -0.629 was reported to exist between WRS and DM HINT RTS (Figure 20). This means that the higher (better) a participant’s WRS the lower their predicted RTS value. All of these correlation values
were found to be statistically significant and it is important to note their potential predictive value for the current sample size.

**Discussion**

Results from the present study revealed no significant differences between unaided, OM, and DM performance. The DM performance provided the lowest (best) overall RTS (Mean = 6.6 dB SD = 3.1 dB), followed by OM performance (Mean = 7.5 dB SD = 3.3 dB), and finally unaided performance (Mean = 7.3 dB SD = 4.6 dB). DM settings resulted in an overall average RTS improvement of 1.3 dB compared to unaided performance. This improvement was not found to be significant. This is in agreement with previous BICROS studies (Williams et al, 2012; Oeding and Valente, 2013) that examined speech recognition in noise of BICROS users in different listening environments. These listening environments included the WIN test, presented at 70 dB SPL (in all test conditions) at 0° azimuth and multi-talker babble noise at 180°, speech at 270° and multi-talker babble noise at 90°, and multi-talker babble noise at 270° with speech presented at 90° (Williams et al, 2012), and HINT sentences from 0° azimuth with uncorrelated Lou Malnati’s restaurant noise presented from 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° at a constant 65 dB SPL (Oeding and Valente, 2013). When comparing the current study to Oeding and Valente (2013) which examined the Tandem 16 BICROS the results revealed no significant difference (p = 0.07) between unaided, minimum Noise Reduction, and maximum noise reduction in a diffuse listening environment. Williams et al (2012) reported no significant difference between the participants own BICROS and the Phonak BICROS with DM active (p > 0.05).

In the current study, participants, on average, performed equally well in all three listening conditions (unaided, OM, and DM) while being tested in a difficult diffuse listening
environment. The diffuse listening environment in the current study is more difficult than the listening environment described in Williams et al (2012) and is identical to the listening environment used in Oeding and Valente (2013). It is for this reason that results from the current study are most easily compared to the findings of Oeding and Valente (2013). That is, participants in the current study performed very similar to participants in Oeding and Valente, (2013) even though the studies were investigating two different features: Noise Reduction in the Tandem 16 BICROS on the transmitter and receiver sides (Oeding and Valente, 2013) and DM on receiver and OM (Real-Ear Sound) on the transmitter side (current study). Both studies performed real ear verification, as did the current study. Oeding and Valente (2013) utilized the many of the same test materials as the current study: HINT testing in the R-SPACE system and the APHAB questionnaire to assess subjective benefit. Williams et al (2012) also investigated objective performance on a speech test in noise, however the WIN test differs greatly from HINT testing in the R-SPACE system in many ways and may be less indicative of performance in real-world situations when compared to HINT testing in the R-SPACE system.

FBR testing involving the OM settings revealed nearly all polar plot measurements in the OM test condition revealed directionality form 1600 Hz to 5000 Hz as can be seen by the polar plot in Figure 12. This directionality may be caused by the “Real-Ear Sound” microphone setting on the receiver. “Real-Ear Sound” is a microphone response/processing algorithm that is designed to shape the frequency response of the BICROS to more closely represent the natural resonance of the human pinna, which is most prominent between 1500 Hz and 6000 Hz. This “Real-Ear Sound” microphone setting is important because the natural gain provided by the pinna is lost when the microphone placement is on top of the pinna compared to in the canal. This setting was chosen as it is the recommended default microphone program. It is possible to
set the “OM” microphone response to either “Real-Ear Sound” or a traditional OM (no
directionality) within Phonak’s software. This directional component is marginal in most cases
and may have only had a minimal affect on the results of the current study. Future studies,
however, could examine differences between OM and Real-Ear Sound.

In the current study a significant correlation between the mean PTA, WRS, and mean
HINT RTS for unaided, OM, and DM was found. The participants who had a poorer PTA
(higher), poorer WRS for the better ear typically had a higher (poorer) RTS than participants
with a lower (better) PTA and better WRS in the better ear. This was true for the majority of
participants in the current study. In contrast, some participants with lower (better) PTA and
better WRS typically had lower (better) RTS for each listening condition. These results suggest
that better hearing in the aided ear of a BICROS user typically indicates a lower (better) RTS.
Eight participants performed significantly better with the DM settings active on the receiver than
in the OM and unaided listening conditions while three performed significantly better in the OM
and/or unaided test conditions. It is unclear why this variation in performance occurred. It was
noted, however, that the majority of participants who performed significantly better in the DM
listening condition had a decreased magnitude of hearing loss in the better hearing ear. It is
important to note, however, that these findings are highly variable not only between participants,
but also between trials within participants. The variation in HINT performance during testing
may be affected adversely by several factors that could not be controlled for or factors that were
not assessed during the current study. These individual factors may include: head movement,
attention deficits specific to each participant, and central auditory processing. Head movement
of the participant could potentially have an adverse affect on HINT testing. The R-SPACE
loudspeaker array is positioned at a calibrated distance from the participant, head movement
would change this distance, subsequently increasing or decreasing the intensity of the sounds arriving from the loudspeaker array. Attention deficits specific to each participant were not assessed in the current study, however, previous studies have shown that individuals with attention deficits perform poorer in environments with background noise present. HINT testing has been included in central auditory processing assessments in the past and any unknown impairment in any participants in the current study may also have adversely affected the HINT testing. All of these factors could potentially have an adverse affect on the results of the assessments, but these factors were not assessed in the current study.

To investigate why the results for the Phonak BICROS differ from those of conventional hearing aids comparing OM to DM, the investigators evaluated the directionality of the receiver with the transmitter active in the test box together. This was completed using the Audioscan Verifit system. First, the receiver was tested in the OM (Real-Ear Sound) and DM (UltraZoom) programs for each participant in the study, as well as in a traditional OM program that was programmed to be identical to the “speech-in-noise” settings. These three settings were tested at the calibrated test point in the test box utilizing a 65 dB SPL speech signal (Figure 21). Then the receiver was placed near the front loudspeaker, placed in the “UltraZoom” DM program and tested once more (Figure 22). Following this the transmitter was placed in the Audioscan Verifit test box near the back loudspeaker (Figure 23). The distance between the receiver and transmitter is similar to that of the distance between ears on a participant. The directional measures were then performed with the transmitter active in all three microphone settings for all 19 participants in the study and averaged across participants. Figure 24 illustrates the FBR performance of DM settings. The difference between the front loudspeaker and rear loudspeaker response indicates the DM is performing well. Figure 25 illustrates FBR measures for OM, DM,
and traditional OM settings. The resulting measures indicate performance for all settings within manufacturer’s specifications. Figure 26 illustrates FBR measures of receiver performance in OM, DM, and traditional OM settings with the transmitter active in the Audioscan test box. A significant difference is noted between microphone performance with the transmitter active compared to inactive. The mean FBR and SD of each condition derived by calculating the output difference at the 16 test frequencies from the left and right loudspeakers in the Audioscan Verifit, then averaging those calculations for each participants settings, then averaging and calculating the SD for those averages. This was done for each program setting. The mean FBR and SD of each condition are 3.8 dB (SD = 1.1 dB) for the “traditional” OM, 8.1 dB (SD = 3.1 dB) with DM inactive (OM condition in test settings), 18.2 dB (SD = 5.1 dB) with UltraZoom, 18.3 dB (SD = 5.2 dB) with receiver only moved to near the front loudspeaker, 1.4 dB (SD = 2.8dB) for “UltraZoom” with the transmitter active, -0.7dB (SD = 1.8 dB) for “Real-Ear Sound” with the transmitter active, and -0.6 dB (SD = 0.9 dB) for “traditional OM” with the transmitter active. These results indicate that when the transmitter is active the output of the receiver represents an OM FBR. These results may explain the lack of significant difference in performance in HINT testing as well as the lack of perceived difference between OM and DM settings by patients reported in the APHAB questionnaire.

Though the findings of the current study did not reveal any significant differences in speech recognition, some subjective preferences were reported by the participants via the APHAB. The mean APHAB benefit score on the EC, RV, and BN subscales revealed statistically significant improvement with the Phonak BICROS compared to unaided listening conditions. APHAB problem scores have been extensively examined in recent studies investigating CROS hearing aids. Oeding and Valente (2013) reported unaided problem scores
near the high end of these CROS study ranges or greater; EC = 46.0%, RV = 70.8%, and BN = 71.8% and BICROS aided problem scores of EC = 15.1%, RV = 30.1%, and BN = 38.7%.

Bosman et al (2003) and Hol et al (2004; 2005) reported unaided problem scores range from 16.7 to 29.0% for EC, 37.7 to 50.0% for RV, and 67.6 to 74.0% for BN and aided problem scores in a range of 12.0 to 20.0% for EC, 30.5 to 40.0% for RV, and 48.0 to 56.0% for BN. Results of CROS benefit scores compared to BICROS, therefore, report less benefit. The authors attributed these variations in problem scores to “the degree of hearing loss in the better ear” which “results in CROS participants having lower (better) unaided SNRs than participants using BICROS” (Oeding and Valente, 2013). Unaided problem scores from the current study were similar to those of Oeding and Valente (2013) with the Tandem 16 BICROS results being 39.6% for EC, 61.5% for BN, and 63.0% for RV subscales and aided problem scores for the Phonak BICROS were reported as follows for each subscale: 13.6% for EC, 28.8% for RV, and 33.8% for BN on the APHAB subscales.

A potential shortcoming of the current research study is the primary investigator’s hearing ability. The primary investigator has utilized a cochlear implant for over 11 years. To account for possible problems with scoring the HINT several practice trials were performed to assess the primary investigator’s ability to accurately assess the responses of the second investigator. These trials yielded consistent results between the primary investigator and the normal hearing secondary investigator. Due to these extensive trials, the authors of this study are confident in the subjective assessment of participant’s responses during HINT testing. An additional potential shortcoming of the current study is the variation reported between participants in the overall wear time of the BICROS as reported by datalogging. Datalogging reports show adequate length of daily use (mean = 10.6 hours/day, SD = 2.8 hours/day) and
balanced program use (“Program 1” mean = 59.3%, SD = 21.5% and “Program 2” mean = 40.7%, SD = 21.5%). It is important to note that the data for program use percentage does not contain entries for three participants. Though there was variation in the amount of time individual participants wore the BICROS, the overall average appears to be typical for use of hearing aids. This should minimize the effects of decreased time of use, however, this low amount of experience (5.2 hours per day and 5.6 hours per day) for two individual participants may have had an adverse affect on the individual participants’ RTS in the two aided (OM and DM) listening conditions due to the lack of acclimation to the sound quality of the BICROS. Five participants had datalogging results reporting significantly lower percentage of use in one program in comparison to the other (range of use 5.8% to 24.3%). It is important to note that this significant difference in program use was balanced between programs, and due to the randomization of program order accounted for the possibility of the same program being used in all five participants. This decreased experience may have contributed to a reduction in RTS average that could not be measured due to an inability to acclimatize to the other program.

Conclusions

Results from the present study did not reveal significant differences in the RTS between unaided, OM, and DM listening conditions in the Phonak BICROS. Participants, however, did perceive a statistically significant benefit with the Phonak BICROS compared to unaided performance on the EC, RV, and BN subscales of the APHAB, but no differences were perceived between OM and DM settings. At this time; six participants chose to purchase the BICROS used in the study, while 11 participants chose batteries for compensation, and two participants were still in a trial period with non-experimental settings.
Based on the results of the current study as well as previous studies examining the performance of DM (Boymans and Dressler, 2000; Nordrum et al, 2006), it is recommended by the authors that hearing aid manufacturers consider an automatic, adaptive multi-channel DM on the transmitter and receiver sides because of the results of the current study. The addition and evaluation of a DM on the receiver and transmitter sides would determine if persons with ASNHL can have improved speech recognition in noise. BICROS technology has been shown to eliminate the head shadow effect; the next challenge to manufacturers is to improve patient’s objective and subjective performance in challenging environments such as background noise.
REFERENCES


Figure 1. Audiogram reporting the mean and ± 1 SD for hearing thresholds (dB HL) in the better ear (♦) and poorer ear (●).
Figure 2. Participant’s years of BICROS experience and current BICROS/hearing aid model.

<table>
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<th>Participant</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Years of Experience</th>
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Key: BTE = behind-the-ear; CRT = canal receiver technology; ITC = in-the-canal; RIC = receiver-in-the-canal
Figure 3. Electroacoustic verification of Phonak Ambra microP and the resulting measures.
Figure 4. Electroacoustic verification of CROS H₂O transmitter. (A) shows the placement of the receiver for testing. (B) shows the placement of the transmitter at the calibrated test point for testing. (C) shows the resulting output response of the measure.

A.

B.

C.
Figure 5. Audioscan Verifit Directionality test.

Select one of Test 1 through Test 4.
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Figure 22. Placement of receiver for FBR testing in the Audioscan Verifit.
Figure 23. Placement of transmitter and receiver for FBR testing in the Audioscan Verifit.
Figure 24. FBR of the “UltraZoom” DM performance of the receiver in the Audioscan Verifit.

Select one of Test 1 through Test 4.
Figure 25. FBR results for the OM and DM settings of the receiver.

Select one of Test 1 through Test 4.
Figure 26. FBR of the receiver in OM, DM, and traditional OM settings with the transmitter active, and with the transmitter inactive in the DM settings.