Speech Perception in Noise Using Directional Microphones in Open-Canal Hearing Aids

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Emily J. Klemp*
Sumitrajit Dhar*†

Abstract

Background: Individuals with impaired hearing find it difficult to understand speech in the presence of background noise—a problem addressed effectively by directional microphones. As open-canal fittings have become increasingly popular in the recent past, so has the debate about the effective directional benefit available from these devices.

Purpose: This study investigates the benefit of directional microphones in two commercially available open-canal behind-the-ear hearing aids using the Hearing in Noise Test (HINT).

Study Sample: Sixteen individuals, between 50 and 85 year of age, with high-frequency bilateral sensorineural hearing loss and no previous hearing aid experience participated in this study.

Data Collection and Analysis: Data Collection and Analysis: Individuals were asked to repeat sentences (presented at 0° azimuth) in the presence of a diffuse-field uncorrelated broadband speech-shaped noise. HINT performance was compared across hearing instruments and conditions using a linear model with repeated measures.

Results: There was a directional advantage of 2.6 dB as compared to the unaided condition. Average performance was worse in the omnidirectional mode as compared to the unaided condition.

Conclusions: These results suggest that directional signal processing should not be precluded in open-canal instruments for listening in noisy environments.

Key Words: Directional, hearing aids, open-canal fitting

Abbreviations: KEMAR = Knowles Electronics Mannequin for Acoustics Research; BTE = behind-the-ear; REKD = real-ear-to-KEMAR difference; NAL-NL1 = National Acoustics Laboratory—Nonlinear 1

Sumario

Antecedentes: Los individuos con alteraciones auditivas encuentran difícil entender el lenguaje en presencia de ruido de fondo – un problema manejado efectivamente con micrófonos direccionales. Conforme se han hecho más populares las adaptaciones de canal abierto en tiempos recientes, también lo es el debate sobre el beneficio direccional efectivo disponible de estos dispositivos.

Propósito: Este estudio investiga el beneficio de los micrófonos direccionales en dos auxiliares auditivos de tipo retroauricular con canal abierto, disponibles comercialmente, utilizando la Prueba de Audición en Ruido (HINT).

Muestra del Estudio: Participaron en el estudio dieciséis individuos, entre 50 y 85 años de edad, con hipoacusia sensorineurales bilaterales en las altas frecuencias y sin experiencia previa en el uso de auxiliares auditivos.

Recolección y Análisis de los Datos: Se le pidió a los individuos que repitieran frases (presentadas a 0° de azimut) en la presencia de un ruido de contorno de lenguaje de campo difuso y ancho de banda no correlacionado El desempeño con el HINT fue comparado entre los diferentes instrumentos auditivos y condiciones, utilizando un modelo lineal con medidas repetidas.

*Department of Communication Sciences and Disorders, Northwestern University, Evanston, IL; †The Hugh Knowles Center, Northwestern University, Evanston, IL

Sumitrajit Dhar, Department of Communication Sciences and Disorders, 2240 North Campus Drive, Northwestern University, Evanston, IL 60208; Phone: 847-491-2470; Fax: 847-491-2523; E-mail: s-dhar@northwestern.edu

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Resultados: Existió una ventaja direccional de 2.6 dB conforme se comparó con la condición no amplificada. El desempeño promedio fue peor en el modo omnidireccional conforme se comparó con la condición no amplificada.

Conclusiones: Estos resultados sugieren que el procesamiento direccional de la señal no debe ser descartado en instrumentos de canal abierto para escuchar en ambientes ruidosos.

Palabras Clave: Direccional, auxiliares auditivos, adaptación de canal abierto

Abreviaturas: KEMAR = Maniquí de Knowles Electronics para Investigación Acústica; BTE = retroauricular; REKD = diferencia de oído real a KEMAR; NAL-NL1 = Laboratorio Nacional de Acústica – No lineal 1

Individuals with near-normal low frequency hearing sensitivity and considerable hearing loss in the frequencies above approximately 2000 Hz have historically been dissatisfied with traditional hearing aids because of complaints related to the low frequencies being too loud (Otto, 2005; Kiessling et al, 2005; Flynn et al, 2006). This perception could be due to overamplification of the low frequencies and/or the occlusion effect, the buildup of sound pressure in the residual ear canal that occurs when body-conducted sound is trapped by a hearing aid or ear mold (Killion et al, 1988; Mueller, 2003). The dilemma of overamplification in the low frequencies is easily overcome by frequency-specific gain controls available in modern hearing aids. However, complaints related to the occlusion effect still persist with traditional hearing aids, either in-the-ear or when coupled with an earmold. Complaints of occlusion are typically alleviated by introduction of larger vents in the shell of in-the-ear hearing aids or in earmolds. However, larger vents bring with them the increased possibility of feedback, in turn leading to a restriction of achievable gain.

An open-canal hearing aid is a relatively new design coupling a smaller behind-the-ear (BTE) or on-the-ear (OTE) hearing aid to the user's ear canal via a nonoccluding signal delivery system. The goal of such coupling is to ameliorate complaints of occlusion. Manufacturers are able to use this simple acoustic solution in today's hearing aids due to the successful integration of digital feedback management. Feedback, with the aperture of the ear canal open, would indeed be the primary factor limiting gain in open-canal devices in the absence of management algorithms. With nonoccluding coupling, small size, and successful feedback management, open-canal devices have rapidly gained popularity with clinicians and patients alike. Most manufacturers have several open-canal models available within their product lines.

The vast majority of open-canal devices are marketed with directional microphones; this design decision justified by the single most common complaint of hearing aid users, that of difficulty understanding speech in the presence of background noise (Kochkin, 2002a, 2002b, 2005). Directional microphones have proven to be the most effective, if not the only, solution to this problem of speech understanding in noise for hearing aid users (see Bentler, 2005, for review). However, the physical acoustics of an open-canal device complicates the utility of a directional microphone. Simply put, in the case of hearing aids, a directional microphone attenuates signals from directions other than that directly in front of the user. In the case of open-canal devices, the question is this: Would this effect be negated by the undesired noise entering the open ear canal? Consistent with this line of thinking, directional advantage has been demonstrated to be inversely related to vent size in hearing aids that are coupled to the canal using traditional earmolds (Ricketts, 2000). However, the issue is further complicated by the integral relationship between vent size and the frequency-specific directivity or directionality of the instrument.

The frequency specificity of directivity of a hearing aid is affected by port spacing in directional microphone systems. Directionality of traditional (occluded canal) hearing aids is maximal at low frequencies (Dillion, 2001). In other words, the sensitivity of a directional microphone system is low for low-frequency signals where the wavelength exceeds the distance between the microphones of an array resulting in minimal differences in the phase of the signal at the different microphones. Vent size is directly proportional to attenuation of low frequencies in the output of the hearing aid (Lybarger, 1985); that is, the larger the vent the lower the output of a hearing aid in the low frequencies. Therefore, directivity in the low frequencies is threatened by the introduction of a large vent or an open sound delivery system, which will also allow direct entry of the environmental noise into the ear canal. Thus, the effectiveness of directional microphones in open-canal devices is influenced by several interdependent variables such as the "openness" of the ear canal, the lack of low-frequency gain thereby limiting low-frequency directivity, and the amount of high-frequency gain and directionality achieved. While open-canal devices with directional features are common in the marketplace, empirical evidence of their efficacy is not.

A few recent reports indicate some evidence of directional benefit in open-canal hearing aids (Goode and Krusmark, 1999; Kuk, et al, 2005; Otto, 2005; Fabry, 2006; Flynn et al, 2006; He et al, 2006; Yanz and Olson, 2006). These reports use subjective (Goode and Krusmark, 1999; Kiessling et al, 2003; Kuk et al, 2005; Otto, 2005; Flynn et al, 2006; Yanz and Olson, 2006), objective

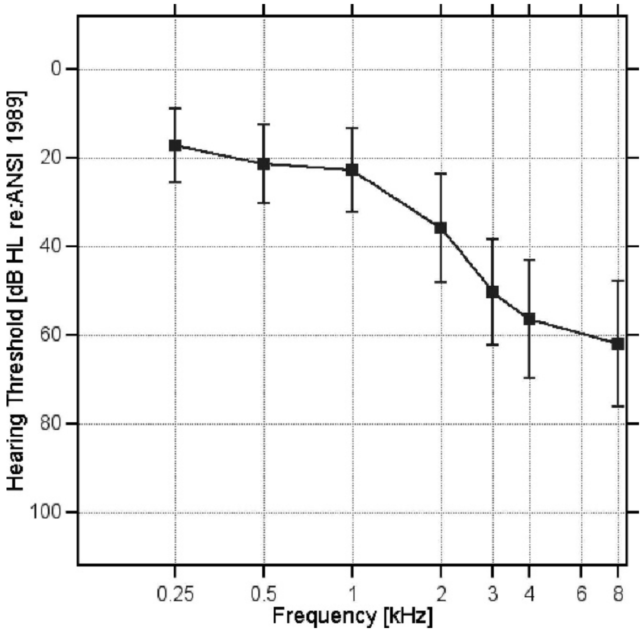

Figure 1. Mean air conduction thresholds of 16 participants. Right and left ear thresholds are pooled in a common average as hearing losses were symmetrical. The error bars represent ±1 standard deviation.

(Kiessling et al, 2003; Kuk et al, 2005; Fabry, 2006; Flynn et al, 2006), and acoustic measures (Bentler et al, 2006; He et al, 2006). In 16 experienced users of hearings aids, Flynn et al (2006) reported a statistically significant directional benefit of 2.92 dB as compared to the omnidirectional setting of the Oticon Corda instrument. Similarly, Kuk et al (2005) reported an average directional benefit of 2.6 dB over the omnidirectional condition in eight individuals using the Widex Diva élan. Finally, Fabry (2006) demonstrated that the average speech reception threshold in 20 individuals using the Phonak MicroSavia deteriorated in the aided condition as compared to the unaided condition. Performance in the unaided condition was restored and further improved by ~1.5 dB in the same group when the pinna and concha resonances were restored algorithmically. A small directional advantage (~0.5 dB) was also reported in acoustic measures on KEMAR (Knowles Electronics Mannequin for Acoustics Research) using jet noise (He et al, 2006).

Open-canal devices are a welcome addition to the hearing aid marketplace, and their popularity is expected to grow significantly in the future. There appears to be clear subjective preference on the part of hearing aid users for these open-canal devices (Flynn et al, 2006; Gnewikow and Moss, 2006; Taylor, 2006; Yanz and Olson, 2006). Our goal was to measure directional performance in comparison with both the unaided and omnidirectional conditions. We attempted to do so by measuring performance of the group using two commercially available open-canal devices on the Hearing in Noise Test (HINT) (Nilsson et al, 1994).

METHODS

Individuals between the ages of 50 and 85 years (n = 16; mean age: 77 yr.; 9 male, 7 female), recruited from the Northwestern University Evanston Hearing Clinic, participated in the experiment. A bilateral sloping SNHL (Figure 1) and no previous hearing aid experience were required for participation. Air-conduction thresholds between 250 and 8000 Hz (including the interoctave 3000 Hz) were obtained. None of the subjects had an air-bone gap greater than 10 dB. Participants were required to attend two experimental sessions. Approximately 25 individuals were approached about participation in the study, and there were no dropouts during the course of the experiment. Recruitment and participation were in accordance to the Institutional Review Board guidelines at Northwestern University.

Two commercially available open-canal BTE hearing aids (Phonak miniValeo 101 AZ and Widex Diva élan SD-9Mé) were used in this investigation. The hearing aids were coupled to the participants' ears using appropriately sized manufacturer-supplied thin tubes in place of a traditional ear hook, and a small flexible ear tip in place of an ear mold. These two hearing aids were chosen as they used similar acoustic coupling to the ear canal but different signal-processing approaches. Moreover, data were available (Fabry, 2006; Kuk et al, 2005) on these or similar instruments that would allow comparative examination of our results.

Real-ear unaided responses from the participant ($REUR_P$) were recorded with the sound source at 0° azimuth using a 65 dB SPL composite signal on the Frye Electronics FONIX 7000 Real Ear Analyzer with the reference microphone turned off. This same measurement was repeated in the open canal of DB100 ear-simulator mounted on a KEMAR ($REUR_K$). The real-ear-to-KEMAR difference ($REUR_P$ - $REUR_K$ = REKD) was computed for each ear of each participant and used to match the hearing aids' frequency response to the NAL-NL1 (National Acoustics Laboratory—Nonlinear 1) target using the Fonix NOAH Module (ver. 1.23). The hearing instruments were programmed on the NOAH platform in the omnidirectional setting without any noise reduction or feedback cancellation algorithm (omni condition). The use of the REKD allowed us to program the hearing aids without active involvement of the participant, allowing us the time to make as many adjustments as necessary. On occasion, a hearing aid programmed on the KEMAR would go into feedback when fit on the participants' ear. The manufacturer-supplied feedback management algorithm was used and the real-ear measurement repeated in such cases. The average deviation from NAL-NL1 targets after initial fitting (and feedback management if necessary) at .5, 1, 2, and 4 kHz are displayed in Figure 2. All data presented in Figure 2 were obtained in the KEMAR

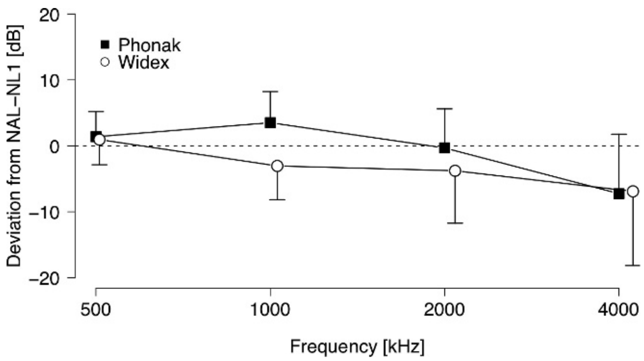

Figure 2. Average deviations of hearing aid output from NAL-NL1 prescriptive targets for the Phonak and Widex instruments. The error bars represent ±1 standard deviation. Data from left and right ears are combined. Negative numbers indicate less available gain to the hearing aid user than prescribed.

with the appropriate correction for individual participants ($REUR_p$).

Speech perception in the presence of background noise was evaluated in the participants under unaided, omni, and three other conditions for each hearing aid. When activated, DIR and/or DNR was set to maximum. If an option, "Hearing Aid Experience" was set to the highest level; "Experience Level" typically affects the overall gain of the hearing aid but should not have affected the output of the devices in this experiment as their gain was set using the NAL-NL1 algorithm. No adjustments to the frequency response were made for the DNR or DIR conditions. We understand that the frequency response, compression, and other electroacoustic characteristics of a hearing aid may change when switched to the DIR or DNR modes. Our goal was to allow all such manufacturer-determined changes to play a role in the speech perception task.

Speech perception in noise in each condition (Table 1) was measured using a modification of the HINT (Nilsson et al, 1994). Two additional channels of noise were added to the original two channels of sentences and noise, thus creating a total of four channels. The first channel carried the speech signal while uncorrelated (time-shifted) versions of the standard speech-shaped noise were presented through the other three channels. The three noise channels were further modified by adding a 12 sec noise lead-in before the onset of each sentence, allowing all signal-processing schema in the hearing aids to be fully activated prior to the presentation of the speech signal. An equivalent 12 sec period of silence was added to the beginning of each sentence in the first channel. The duration of the lead-in was chosen for efficiency and to make our results comparable to our earlier work (Nordrum et al, 2006). The duration of the lead-in may not have been sufficient to fully activate all signal-processing schema in both hearing aids. In such cases our results would not represent accurate estimates of the effects of such

Table 1. Conditions for the Evaluation of Speech Perception in Noise

Cond.	Code	*DIR*	*DNR*
U	Unaided		
W_i	Omni	-	-
W_{ii}	DNR	-	+
W_{iii}	DIR	+	-
W_{iv}	Both	+	+
P_i	Omni	-	-
P_{ii}	DNR	-	+
P_{iii}	DIR	+	-
P_{iv}	Both	+	+

Note: W = Widex Diva élan SD-9Mé; *P* = Phonak miniValeo 101AZ; + = activation of a particular feature.

algorithms on speech perception in the presence of background noise. However, as will be seen later, our results are in good agreement with those obtained by Kuk et al (2005) where a longer lead-in time was used.

The signals (speech and noise) were delivered through four channels of an M-Audio Quattro input/output USB device from the hard disk of a computer. Presentation was controlled on a computer using the sound editing software package, Tracktion 2.0™. The sentences were presented from a speaker at 0° azimuth, and the three channels of uncorrelated noise were presented from matched speakers at 90, 180, and 270° azimuth. Realistic Minimus speakers were used for signal delivery and placed at a height of 0.91 m from the floor and 1 m from the participant's seat. Presentation levels were calibrated to the participant's chair (at approximately ear level) using the calibration tracks provided with the HINT compact disc. The measurements were conducted in a double-walled audiometric test booth with reverberation times significantly lower than those encountered by hearing aid users in the real world. Reverberation and the nature of noise in the background noise field are critical variables in determining the correspondence of laboratory results with performance in the real world (Bentler, 2005; Dittberner and Bentler, 2007).

The HINT test is an adaptive speech in noise test, with sentence presentation levels varied based on performance accuracy (i.e., a correct response causes a reduction in presentation level by 2 dB, while an incorrect response causes an increase in the presentation level by the same amount). A step size of 4 dB is used for the initial five sentences in a block, which are not used in the computation of the SNR threshold. The speech-shaped noise was kept fixed at a constant 65 dBA. Two blocks of ten sentences were used for each condition. As per protocol, the presentation level for the 21st sentence was assigned based on the response to the last sentence of the second block; however, a 21st sentence was never presented. The noise level (65 dBA) was subtracted from the average presentation levels for sentences 5 through 21 to compute the SNR threshold for each condition.

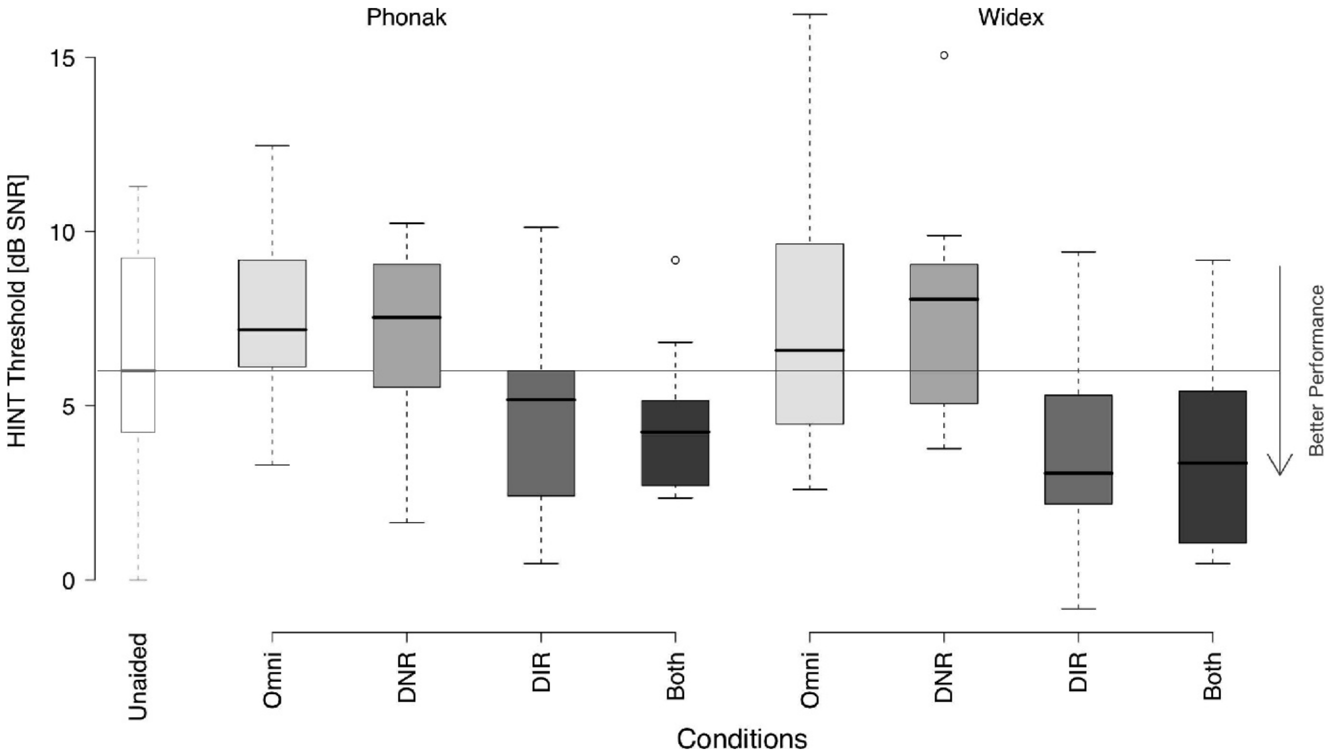

Figure 3. HINT thresholds in dB SNR of the 16 subjects for each instrument and condition in the box and whisker plot format. The boxes represent the interquartile range (IQR) with the median shown in the solid line inside each box. The whiskers extend to the maximum and minimum when within 1.5 times the IQR. Data beyond this range are shown with individual symbols. The solid horizontal line across the entire graph represents the median unaided HINT performance.

The unaided condition was administered first for each participant. Hearing aids, the conditions within each hearing aid, and the modified HINT lists used were counterbalanced across participants.

HINT performance was statistically compared across hearing aids and conditions using a general linear model with repeated measures. HINT benefit for the DIR, DNR, and both conditions were compared independently with reference to the unaided and omni conditions using independent general linear models with repeated measures. Individual hearing aids and the conditions within each hearing aid were the factors used in the primary analysis. Comparison of individual conditions was made using a Tukey (HSD) post hoc analysis. All statistical tests were performed using the R software package version 2.5.1 (R Development Core Team).

RESULTS

Mean hearing thresholds (left and right ears pooled) from the participants (N = 16) are displayed in Figure 1. The average hearing loss profile is that of a bilateral moderate to moderately severe SNHL, with near normal thresholds below 1 kHz. Each of these individuals was fit binaurally using targets from the NAL-NL1 algorithm. Average deviations from the NAL-NL1 target after feedback management where necessary are displayed in Figure 2. The average deviation from target varied from approximately 1.5 dB at 500 Hz to 7 dB at 4 kHz. These deviations reflect the combined effects of the initial fitting and subsequent feedback management where necessary. The deviation from target is greatest at 4 kHz, reflective of the limit to maximum gain allowed by each instrument following feedback management.

Performance on the HINT for each instrument and condition is displayed in Figure 3. The median unaided HINT threshold was 6 dB in contrast to the normative average value of approximately −3 dB in a normal-hearing population (Nilsson et al, 1994). A horizontal line across the entire graph marks this median performance in the unaided condition. Smaller HINT thresholds indicate that 50% performance was achieved at lower SNRs and signify better performance. Thus, performance deteriorated in conditions that required an SNR greater than the unaided threshold—the omni and DNR conditions for both hearing aids. The results of the repeated measures ANOVA showed a main effect for condition (*p* < 0.001) but not for hearing aids when data were pooled across conditions. Performance across hearing aids was equivalent even though there were differences in the average output of the devices as observed in Figure 2.

Statistical significance of differences between conditions was evaluated using a Tukey HSD procedure using an adjusted criterion level of 0.05. Each combination of hearing aid and condition along with the unaided condition

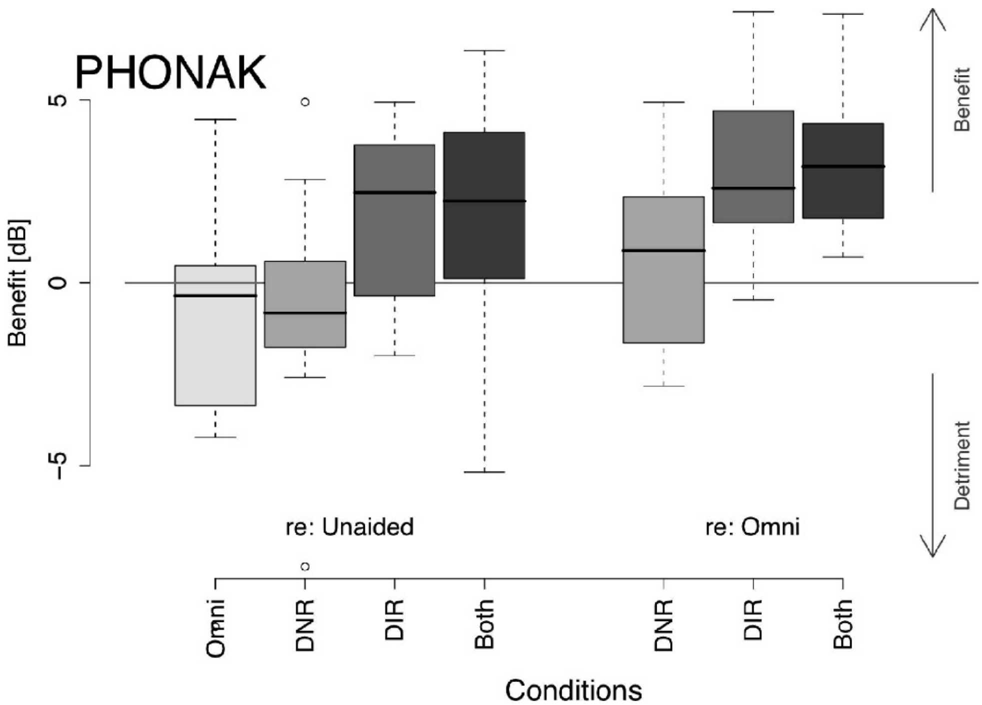

Figure 4. Benefit or detriment derived when using each condition for the Phonak instruments referenced to either the unaided or the omni conditions. The box and whisker plot is similar in format to Figure 3. Data on the positive half of the ordinate represent benefit, while those on the negative half represent detriment.

resulted in thirty-six comparisons across nine testing levels. Of primary interest were differences between the omni condition and the DNR, DIR, or both conditions. A statistically significant difference was observed between the omni and the DIR conditions (DIR better than omni) for the Phonak and Widex instruments (adjusted $p < 0.001$). Additionally, the DNR condition was significantly different from the DIR and both conditions (DIR/both better than DNR) for the Widex but not for the Phonak instrument. Notably, neither the DIR nor the both

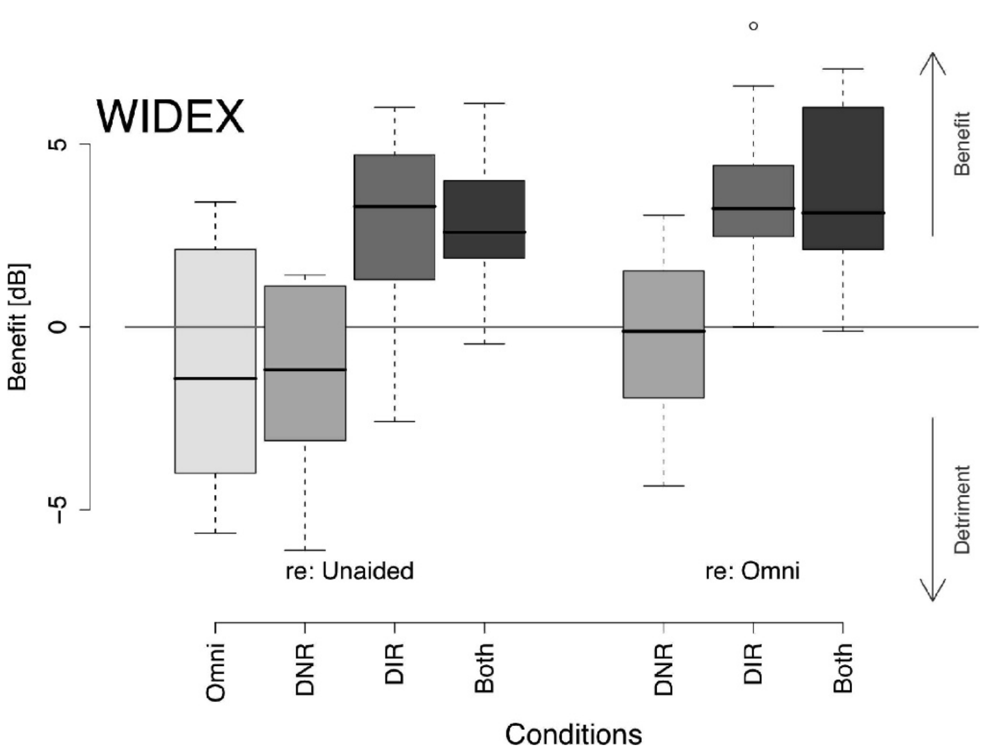

Figure 5. Same as Figure 4 but for the Widex instrument.

conditions were statistically significantly different from the unaided condition for either hearing aid.

The differences between conditions calculated as *benefit* (as opposed to performance) are displayed in Figures 4 (Phonak) and 5 (Widex). In the left and right halves of each figure, performance in the unaided and omni conditions is used as the reference, respectively. Using this metric, positive numbers signify benefit as compared to either the unaided or omni conditions. On the other hand, negative numbers indicate a degradation of performance, as seen in the omni and DNR conditions when compared to the unaided measure in both hearing instruments. Pooling the results from both hearing aids, a mean improvement of 2.26 dB was observed in the HINT for the DIR condition as compared to the unaided condition. Notably, the mean difference between the DIR and omni conditions was bigger (3.32 dB) and statistically significant ($p < 0.0001$). This is consistent with a degradation of performance in the omni condition, making the benefit larger when switching from omnidirectional to directional microphones.

In summary, speech understanding in noise suffers when an open-canal high-frequency emphasis hearing aid is used without any directional signal processing, though performance can be improved over the unaided condition if a directional signal processing strategy is used.

DISCUSSION

The focus of this study was to assess the benefit of directional microphones in open-canal hearing aids. We used performance on the HINT under various conditions as the HINT has been used in a wide variety of studies measuring directional performance and benefit (see Bentler, 2005). It should be noted that the population of hearing aid users in these previous studies typically involved individuals with greater degrees of hearing loss, especially at low frequencies. Thus, these individuals were utilizing both amplification and directivity in the low frequencies provided by the hearing instruments. The participants in studies involving open-canal hearing aids (including ours) do not rely on the hearing aid for amplification of the low frequencies. Consequently low-frequency directivity due to the hearing instruments is not available to this population.

Each participant was fit with the devices under evaluation using the NAL-NL1 algorithm. The reader is reminded that we verified the fit for the omni condition (omnidirectional without digital noise reduction). We are cognizant that multiple electroacoustic characteristics are often automatically adjusted when these features are activated on hearing aids (e.g., frequency response, compression). Our goal was to evaluate the performance of the instruments including programmatic alterations that accompany either directionality or noise reduction. Thus, we did not alter the frequency response of the instruments once these features were activated. The maximum gain of the devices was limited especially in the high frequencies following feedback management (Figure 2). Thus, reduced audibility in the high frequencies possibly had a detrimental effect on the subjects' performance. Further, there were small differences in the average output of the two devices at 1 and 2 kHz. These differences did not lead to any significant differences in average performance under any condition between the two hearing aids.

The traditional comparison for directional performance in hearing aids has been omnidirectional performance. However, as mentioned by Fabry (2006), this may not be a clinically valid comparison for this population with relatively intact low-frequency hearing (see Figure 1). In other words, the candidate group for the hearing aids evaluated here is relatively less effected by hearing loss and may perform at a higher level (without hearing aids) than the traditional hearing aid user. Thus, one important concern would be to not put the user at any further disadvantage when trying to understand speech in noise using an open-canal device. Our results appear to confirm this suspicion, in that performance using either hearing aid deteriorated in the omni and DNR conditions as compared to the unaided condition.

These results confirm that directional benefit is smaller in open-canal hearing aids as compared to traditional occluded fittings. A recent study (Nordrum et al, 2006) using the identical procedures has reported a directional advantage of 3.5 dB over omnidirectional conditions using closed-canal devices. We report a smaller and statistically nonsignificant benefit of 3.32 dB using a similar comparison. However, of greater importance are the observations of degradation of performance in the omni and DNR conditions compared to the unaided condition, and the smaller benefit of approximately 2.64 dB in the DIR condition as compared to the unaided condition. When data are pooled across the two hearing aids, there was an average ~1.25 dB deterioration of performance on the HINT by using the hearing aid in omnidirectional mode as compared to unaided performance. This drop in performance could be attributed to the loss of high-frequency directivity of the open ear due to using the omnidirectional hearing aid. This loss was not recovered by the use of DNR alone but was more than compensated for by use of directional microphones either alone or in conjunction with digital noise reduction. The deterioration in performance in the omni condition as compared to the unaided condition is particularly relevant to open-canal devices. As users of closed-canal devices typically have larger hearing losses (especially at low frequencies), the need for audibility may trump the need for directionality in those cases. Thus, omnidirectional performance is typically better than unaided performance in users of closed-canal devices, provided they have a sufficiently significant hearing loss.

The relatively intact low-frequency hearing of the participants appears to adequately handle competing noise in the low frequencies, allowing the participants to successfully use the high-frequency directivity available in open-canal instruments. Thus high-frequency directivity is of utmost importance in open-canal devices. Directivity in open-canal instruments is attained through engineering solutions such as smaller port spacing between microphones. Rapid innovation in the hearing aid market place has ensured that open-canal hearing instruments have evolved since the initiation of this project. It would be of interest to examine if directivity in the high frequencies has continued to improve in later-generation devices and whether this improvement in directivity is translated to an equivalent directional advantage for users of these devices.

It is also worth pointing out that directivity decreases as a function of increasing noise level in open-canal devices as more and more of the competing noise enters the system through the direct route of the open canal (Bentler et al, 2006). Compression characteristics of the hearing aid prevent the electroacoustic output to grow at the same rate thereby reducing the effective SNR at the tympanic membrane. Thus, directional benefit is predicted to reduce with increasing background noise level. This trend, of course, cannot be discerned from our data as the noise level was fixed at 65 dBA for all measurements.

In conclusion, we have confirmed that the directional benefit is smaller in open-canal devices as compared to traditional occluded-canal instruments. However, we have also demonstrated the benefit of directionality in open-canal devices as speech understanding in noise appears to get worse when such a device is used with an omnidirectional microphone. Our results should be interpreted with the usual caution regarding differences between performance in a sound-treated audiometric booth and the real world.

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