2006

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J Am Acad Audiol 17:398–412 (2006)

Effect of Type of Noise and Loudspeaker Array on the Performance of Omnidirectional and Directional Microphones

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Abstract

Differences in performance between omnidirectional and directional microphones were evaluated between two loudspeaker conditions (single loudspeaker at 180°; diffuse using eight loudspeakers set 45° apart) and two types of noise (steady-state HINT noise; R-Space™ restaurant noise). Twenty-five participants were fit bilaterally with Phonak Perseo hearing aids using the manufacturer's recommended procedure. After wearing the hearing aids for one week, the parameters were fine-tuned based on subjective comments. Four weeks later, differences in performance between omnidirectional and directional microphones were assessed using HINT sentences presented at 0° with the two types of background noise held constant at 65 dBA and under the two loudspeaker conditions.

Results revealed significant differences in Reception Thresholds for Sentences (RTS in dB) where directional performance was significantly better than omnidirectional. Performance in the 180° condition was significantly better than the diffuse condition, and performance was significantly better using the HINT noise in comparison to the R-Space restaurant noise. In addition, results revealed that *within* each loudspeaker array, performance was significantly better for the directional microphone. Looking *across* loudspeaker arrays, however, significant differences were not present in omnidirectional performance, but directional performance was significantly better in the 180° condition when compared to the diffuse condition. These findings are discussed in terms of results reported in the past and counseling patients on the potential advantages of directional microphones as the listening situation and type of noise changes.

Key Words: Behind-the-ear (BTE), directional benefit, directional microphone, Hearing in Noise Test (HINT), in-the-canal (ITC), omnidirectional microphone, Phonak Perseo, R-Space™ restaurant noise

Abbreviations: AI-DI = articulation index-directivity index; BTE = behind-the-ear; HINT = Hearing in Noise Test; ITC = in-the-canal; ITE = in-the-ear; MIL = most intelligible level; NAL-NL1 = National Acoustics Laboratories—Non-Linear (Version 1); RTS = reception threshold for sentences; SNR = signal-to-noise ratio

Sumario

Se evaluaron las diferencias en desempeño entre micrófonos omnidireccionales y direccionales utilizando dos condiciones de altoparlantes (altoparlante único a 180°; difuso utilizando ocho parlantes colocados a 45° entre sí) y con dos tipos de ruidos (ruido HINT de estado estable; ruido de restaurante R-Space™), Se les colocaron auxiliares auditivos Phonak Perseo bilateralmente

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a veinticinco participantes utilizando el procedimiento recomendado por el fabricante. Luego de usar los auxiliares por una semana, se afinaron los parámetros de acuerdo a comentarios subjetivos. Cuatro semanas después, se evaluaron las diferencias entre los micrófonos omnidireccionales y direccionales usando frases HINT, presentadas a 0°, manteniendo constantes los dos tipos de ruido de fondo a 65 dB A y en la condición de dos altoparlantes. Los resultados revelaron diferencias significativas en Umbral de Recepción para Frases (RTS en dB) donde el desempeño direccional fue significativamente mejor que el omnidireccional. El desempeño en la condición de 180° fue significativamente mejor que en la condición difusa, y el desempeño fue significativamente mejor usando el ruido HINT en comparación con el ruido de restaurante R-Space™. Además, los resultados revelaron que dentro de cada arreglo de altoparlantes, el desempeño fue significativamente mejor para el micrófono direccional. Considerando los diferentes arreglos de altoparlantes, sin embargo, no se hallaron diferentes significativas en el desempeño omidireccional, pero el desempeño con direccionales fue significativamente mejor en la condición de 180, cuando se comparó con la condición difusa. Estos hallazgos se discuten en términos de los resultados reportados en el pasado, así como en función de orientar a los pacientes sobre las ventajas potenciales de los micrófonos direccionales, conforme la condición de escucha y los tipos de ruido cambian.

Palabras Clave: Retroauricular (BTE), beneficio direccional, micrófono direccional, Prueba de Audición en Ruido (HINT), en el canal (ITC), micrófono omnidireccional, Phonak Perseo, ruido de restaurante R-Space™

Abreviaturas: AI-DI = índice de articulación-índice de direccionalidad; BTE = retroauricular; HINT = Prueba de Audición en Ruido; ITC = en el canal; ITE = intra-auricular; MIL = nivel más inteligible; NAL-NL1 = Laboratorios Nacionales de Acústica – No lineal (Versión 1); RTS = Nivel de recepción de frases; SNR = tasa señal/ruido

In recent years, there has been a resurgence of interest in hearing aids with directional microphones. This is because directional microphones have been reported to significantly improve (re: omnidirectional performance) the speech recognition ability of hearing-impaired patients in moderately noisy listening environments when evaluated in the laboratory (Valente et al, 1995; Preves et al, 1999; Ricketts and Dhar, 1999; Pumford et al, 2000; Ricketts, 2000b; Valente et al, 2000).

Recently, the hearing aid industry incorporated digital signal processing (DSP) techniques into the design of directional hearing aids and introduced *adaptive* directional microphones. In these microphone systems, the polar pattern of the directional microphone changes automatically in response to signals arriving at different azimuths. This may mean a cardioid pattern for a single noise source presented directly from behind or bidirectional when the noise source is at the side. In a more diffuse noisy situation, where the noise source originates from everywhere *but the front*, the system assumes a polar pattern (typically, hypercardioid) that minimizes the intensity of the noise from all noise azimuths arriving from behind. This advancement theoretically ensures the best signal-to-noise ratio (SNR) regardless of the azimuth of the noise. In spite of this advance, adaptive directional microphones may not always provide improved benefit (re: fixed directional polar design). Research has suggested, however, that adaptive microphones never provide poorer performance than fixed arrays (Ricketts and Henry, 2002; Boymans, 2003).

Recently, Phonak introduced its digital hearing aid in which one feature is an adaptive directional microphone. This adaptive microphone reportedly ensures identical sensitivity and phase characteristics of the dual microphones and a mechanism to *automatically* change the polar pattern from omnidirectional to any directional pattern while compensating for the changes in low-frequency response associated with each pattern. This hearing aid can be programmed to a *fixed* hypercardioid directional or omnidirectional mode. The automatic adaptive mode, however, is typically the default setting when the hearing aids are programmed. While theoretically appealing, the performance of the default adaptive microphone in this hearing aid has not been compared to its omnidirectional counterpart nor has its effectiveness been compared when noise sources are generated from the sides, back, and front.

When evaluating the efficacy of microphone performance, laboratory benefits should ideally be accompanied by real-world benefits in order to establish the effectiveness of microphone performance. Recently, a multichannel, eight loudspeaker soundfield system (i.e., R-Space™) has been introduced that accurately recorded and then reproduced/simulated a real-world restaurant for hearing aid evaluations (Revit et al, 2002). A recent study by Compton-Conley et al (2004) reported that the performance of omnidirectional and directional microphones were similar when measured "Live" and in the "laboratory" and when using this system. Thus, this new system may provide the researcher and clinician with a tool that provides greater external validity of hearing aid performance when measured in the laboratory or clinic. This may provide the clinician with information that has greater predictive power on expected performance of hearing aids in noise than has been available in the past. It could be beneficial to clinicians to measure differences in hearing aid performance using a more real-world type noise and loudspeaker array in comparison to a noise (i.e., steady-state HINT noise) and loudspeaker array (single loudspeaker behind or multiple loudspeakers at the side and back) that have been commonly used in hearing aid research over the past decade.

The primary objectives of the present study were to determine if:

1. Significant differences were present in the reception threshold for sentences (RTS in dB) required for 50% performance on the Hearing in Noise Test (HINT) sentences presented at 0° and the noise level fixed at 65 dBA between omnidirectional and adaptive directional modes.
2. Significant differences were present in the RTS required for 50% performance on the HINT sentences under two loudspeaker arrays (180°; and 0, 45, 90, 180, 225, 270, 315, and 360°), referred to as "diffuse" for the remainder of the paper.
3. Significant differences were present in the RTS required for 50% performance on the HINT sentences mixed with two types of noise (HINT and R-Space restaurant).
4. Significant differences were present in the RTS required for 50% performance on the HINT sentences for the three two-factor and one three-factor interactions.

PROCEDURES

Participants

Twenty-five adults (13 males;12 females; mean age = 71.2 years [SD = 9.9 years]) with mild-to-moderate severe bilateral symmetrical sensorineural hearing loss (ANSI-1996) at 250–4000 Hz were included in the study. The magnitude of hearing loss was within the recommended fitting range for the experimental BTE (behind the ear) and custom hearing aids. If the subject had bilateral BTE hearing aids entering the study, he or she was fit bilaterally with BTE hearing aids. If the subject had bilateral custom hearing aids entering the study, he or she was fit bilaterally with custom hearing aids. For this study, eight participants were fit bilaterally with BTEs, and 17 were fit bilaterally with custom products (5 ITE [in the ear]; 12 ITC [in the canal]). Mean earphone word-recognition scores (recorded female NU-6 word lists) at the most intelligible level (MIL) were 81% (SD = 12.2%) and 82.5% (SD = 11.3%) for the right and left ear respectively. The presentation level to assess word recognition at MIL was determined by monitored live voice presentation (voice peaking at 0 on the VU meter) of conversational speech and asking the subject to indicate when the presentation level is comfortably loud and most intelligible. Figure 1 reports the mean (and +/- one SD) hearing thresholds at 250 to 8000 Hz average for each ear because t-tests reported no significant differences in mean thresholds between ears at each test frequency. Normal middle ear function was verified via tympanometry using a 220 Hz probe tone if the audiogram revealed an air-bone gap. All participants had prior experience with bilateral amplification for at least six months with their current hearing aids.

When participants were recruited for the study, they were informed that the purpose of the study was to evaluate the performance of a new hearing aid. Participants were not informed about the signal processing or any other aspect of the experimental hearing aid. Finally, to compensate the participants for their efforts, participants were offered the option to purchase the experimental hearing aids at a 30% discount at the conclusion of the study or receive compensation of $300.

Participants were informed that the 30% discount would provide a net savings off the cost of the hearing aids that would be significantly greater than the $300 lump sum payment. All participants signed the Investigational Review Board (IRB) approved informed consent.

Fitting the Experimental Hearing Aids

The experimental hearing aids were initially fit using the manufacturer's recommended "First-Fit" algorithm. Briefly, the hearing aids were coupled to the NOAH Hi-Pro interface box and then placed in the ear canal. In order for the ITE hearing aid fit to be appropriate for the study, the alignment of the two microphones could not exceed 150 from the horizontal plane. Additionally, the two microphone openings could not be hidden by the tragus or pinna ridge. These criteria were checked at the initial fitting. If these criteria were not met, a remake of the hearing aid was requested. For the participants included in this study, eight were fit with BTE, six with full shell ITE, and eleven with half shell ITE. The articulation index-directivity index (AI-DI) of the models used in the present study were measured across the horizontal plane using a KEMAR manikin with Zwislocki coupler in an anechoic chamber ("KEMAR measure" using the terminology suggested by Bentler et al, 2004). Using the one-third octave band importance functions for short passages of the Speech Intelligibility Index (SII) (ANSI S3.5-1997), the AI-DI is 3.8 dB and 3.5 dB for the ITE and BTE, respectively measured at 200, 500,1000, 1600, 2500, and 5000 Hz. Also, the polar plot for the fixed directional microphone position (beta of 0.4 for the ITE; 0.3 for the BTE) revealed a hypercardioid design.

Ideally, the vent diameter of the hearing aids/earmolds should be as small as possible in order to "retain" the directional benefit of directional microphones. Ricketts (2000a) has shown that the DI below 1000 Hz decreased as vent diameter increased. On the other hand, a hearing aid without venting or a pressure vent may not be acceptable to the user because of the occlusion effect. Consequently, a vent guideline was followed where vent diameter was selected based on the hearing loss at 500 Hz. For hearing loss ≤30 dB, a vent diameter of 2 mm was used. The vent diameter was reduced by 0.5 mm for every 10 dB increase in hearing loss at 500 Hz. For the participants in this study, 8% had a hearing loss at 500 Hz between 35–40 (1.5 mm vent); 12% had a hearing loss between 40–50 dB (1.0 mm vent); and 4% had a hearing loss of 60 dB or greater (pressure vent). Thus, 76% of the participants had a hearing loss of ≤30 dB, and a 2 mm was used. The decision to provide a wider vent could reduce the magnitude of the directional benefit reported in this study. In view of the potential occlusion effect with hearing aid

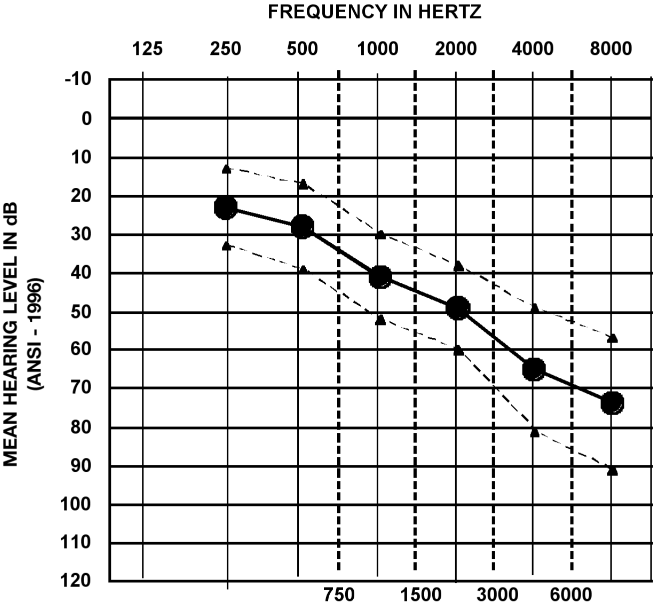

Figure 1. Mean hearing thresholds averaged for the right and left ears. The dashed (▲) lines represent +/- one standard deviation (SD).

use, the current vent recommendation represented a compromise between real-world use of the hearing aid and acceptable directional benefit.

The Phonak fitting software (Version 8.3) was used to program the hearing aids. First, hearing thresholds were entered into the NOAH software. The manufacturer's prescribed "First-Fit" was calculated from these hearing thresholds. The default settings in each of the software "personal system" menus (provides adjustments to the "First-Fit" for prior experience; occlusion effect and feedback) were utilized. If the patient reported occlusion, then this feature was activated. If feedback was noticed, the feedback manager was accessed. All hearing aids were programmed with the adaptive directional microphone as the default setting. It is assumed this is the manner in which hearing aids with adaptive microphones are typically dispensed. Thus, it is important for the reader to understand that the purpose of the study *was not* to evaluate the effectiveness of the adaptive microphone to its fixed counterpart but, rather, to evaluate the effectiveness of the default adaptive directional microphone and how its performance compares to its omnidirectional performance (i.e., benefit).

The participants wore the hearing aids for one week using the manufacturer calculated "First Fit." Then, the aids were reprogrammed (i.e., "adjusted fitting") to address subjective concerns. Figure 2 reports the mean difference in measured adjusted real ear insertion gain (REIG) for the right and left hearing aids relative to the NAL-NL1 (National Acoustics Laboratories—Non-Linear (Version 1); Dillion et al, 1998) prescriptive target for a 70 dB input level. The values appearing at the top of Figure 2 represent the standard deviation. Measures were made with the real ear loudspeaker at 0° azimuth using continuous speech composite noise presented for less than one second. The mean adjusted REIG for each ear was within 6 dB of NAL-NL1 at all discrete frequencies with the exception for 1000 Hz. As can be seen, the fit adjusted to accommodate subject preferences was rather close to the NAL-NL1 target for a 70 dB SPL input level. Unfortunately, real-ear measures were not made for the "First-Fit," and therefore, the difference in REIG between the "First" and "Adjusted" fits is unknown. At this point, participants wore the aids for four weeks before returning for measuring speech perception in noise.

Hearing in Noise Test (HINT)

The HINT (Nilsson et al, 1994) consists of 250 sentences (25 lists of 10 sentences per list) read by a male speaker. The sentences are of approximately equal length (six to eight syllables) and difficulty (first-grade reading level) and have been digitally recorded for

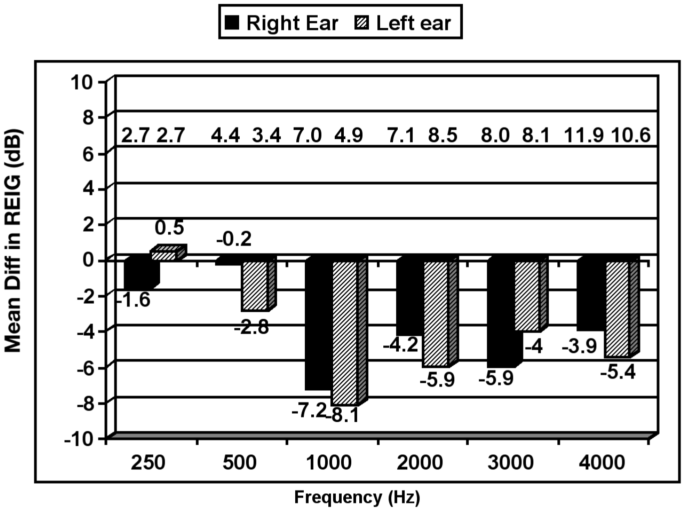

Figure 2. Mean differences in real ear insertion gain for the right and left hearing aids re: NAL-NL1 (Dillon et al, 1998). The values at top represent the SD.

standardized presentation. The HINT estimates the SNR at which the sentences, embedded in noise, can be repeated correctly 50% of the time. This type of measure is useful because it enables accurate, reliable estimation of speech recognition in noise for context-rich speech materials.

The administration of the HINT requires two lists to be presented (20 sentences each) for each experimental condition. The first sentence was presented 10 dB below the attenuator setting necessary for the noise to be presented at 65 dBA. 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 presented. Stimulus level was raised (incorrect response) or lowered (correct response) by 4 dB after the subject's response to the second, third, and fourth sentences. The step size was reduced to 2 dB after the fourth sentence, and a simple up-down stepping rule was continued for the remaining 15 sentences. The calculation of the SNR necessary for 50% sentence recognition was based on averaging the presentation level of sentences 5 through 20, plus the calculated intensity for the twenty-first presentation.

HINT RTS were obtained for two loudspeaker conditions ([a] 180° and [b] diffuse), two microphone conditions (omnidirectional and adaptive directional), and two types of noise sources (HINT and R-Space restaurant). All eight (microphone x loudspeaker x noise type) experimental conditions were randomly assigned to avoid order effects. In addition, sentence lists were counterbalanced to reduce potential learning effects.

Recording the R-Space Restaurant Noise

A known noisy restaurant (noise floor of 58 dBA at the recording position, but may be of little interest because the level of the noise created by the assemblage of people was significantly higher), with carpeted floors, wooden walls, and a wooden cathedral ceiling, was secured for a private party. The dimensions of the room where the recording was made were 36 feet (length) x 36 feet (width) x 8.5 to 17.5 feet (height with a sloping roofline). Thus, the volume of the room was 22,000 cubic feet. The reverberation time is unknown but is probably of limited interest here, because the test materials (HINT sentences) were not spoken in the restaurant and therefore were not subject to any possible masking effects of reverberation. Finally, it was determined that the critical distance for the recording was about five feet. Some of the tables (those nearest the recording position) were partially at or within the critical distance of the recording microphones, but many of the tables were beyond. Therefore, the restaurant simulation was a combination of direct and diffuse elements (L. Revit, pers. comm.). About 45 people were seated and served breakfast in the main seating area of the restaurant, which, when completely full, could accommodate over 100 customers. A table at the center of the main seating area had been removed and replaced by an array of recording microphones. The eight main recording microphones were of the highly directional, "shotgun" (interference-tube) variety, typically used in the movie-making industry to record sounds from a distance. Because each shotgun microphone had a frontal pickup pattern spanning approximately 45° (+/- 22.5°) around its axis, the eight microphones, when placed in an equally spaced, horizontal, circular array, picked up sounds arriving from all horizontal directions around the center of the array. The presumed pick-up points (diaphragms) of the shotgun microphones were located two feet from the center of the array. A ninth, omnidirectional microphone was placed at the center of the array for calibration purposes.

Each microphone was connected via a preamplifier to a separate track of a multitrack, digital audio tape recorder (Tascam DTRS system). In this way, direct and reverberated sounds were captured (recorded) from around the restaurant "on their way" to the center of the two-foot-diameter microphone array. Later, using the R-Space playback system in the laboratory, these "captured" sounds were then released by the eight loudspeakers of the two-foot-diameter playback array. In this way, the sounds that had been captured at two feet from the center of the array in the restaurant could now complete their paths toward the central listening position, although now in a different time and place.

Calibrating the R-Space Restaurant Noise

Before the recording of the breakfast party, calibration signals were recorded individually through each microphone so that playback levels could later be established to reflect the sound levels recorded in the restaurant. Separately for each shotgun microphone, an equalized loudspeaker (flat from 100–16,000 Hz in 1/3-octave bands, +/-3 dB) was held at a distance of two feet in front of the diaphragm, along the center of the pickup axis of the microphone. A pink-noise signal was delivered to the loudspeaker and adjusted to produce 84 dB SPL at the center of the array. For each shotgun microphone, the individual, pink-noise calibration signal was recorded onto the corresponding tape channel. In subsequent playback, the gain of the amplifier for each R-Space loudspeaker was adjusted to produce 84 dB SPL at the center of the loudspeaker array, thus mirroring the calibration recording condition.

On average, the sound-pressure level of the breakfast party, as measured at the calibration point in the restaurant, was 75 dB SPLC, or 72 dB SPLA. Therefore, when properly calibrated, the playback system created corresponding average sound-pressure levels.

The HINT materials (sentences and noise) and the "R-Space restaurant noise" were transferred to a Macintosh hard drive using Toast 5.0 software, before being imported into AudioDesk software. Then, in AudioDesk, the right track was separated from the left track, and the two tracks were digitally spliced end-to-end to form one long "sound bite." This concatenated sound bite was repeated as many times as necessary to provide noise long enough for the longest presentation for the first HINT sentence in the 180° condition. For subsequent HINT lists, the same noise sound bite was used, but with the starting time differing from that of the previous list by several seconds. For the diffuse noise condition, offset times of several seconds were digitally edited and placed in the appropriate channels, thus producing uncorrelated noise for these multiple loudspeaker conditions. Compton-Conley et al (2004, figure 4, p. 447) recently reported that the average long-term speech spectrum of the R-Space restaurant noise was very similar to the average long-term speech spectrum of the HINT sentences and noise.

Figure 3 illustrates the signal presentation system consisting of eight Boston Acoustics CR-65 loudspeakers (dimensions: 257 mm x 162 mm x 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) placed in an equally spaced array at ear level, one meter from the test subject in a 1.97 x 2.54 x 2.73 meter double-walled sound suite (volume = 14.05 m^3) with a reported reverberation time of 0.19 seconds (pers. comm. with Industrial Acoustics Company). The radius of the circle was one meter plus the depth of the loudspeaker (200 mm). The reader is reminded that the one-meter loudspeaker distance used in this study is not the two feet distance suggested for the R-Space. It is reported by the manufacturer (L. Revit, pers. comm.), however, that the impact on measured results of using the one-meter distance for placement of the loudspeakers would be minor.

Prior to testing, two measurements were made using narrow bands of pink-noise centered at 250, 500, 1000, 2000, and 4000 Hz from each of the eight loudspeakers. One measure was made at one meter and the second measure at a half a meter. As expected, the SPL measured at a half meter was 6 dB (+/- 1 dB) greater than the SPL measured at one meter with the exception of 250 Hz for the loudspeakers at 45, 90, 270, and 317°. Thus, for the majority of loudspeakers and frequencies between 500 and 4000 Hz, the subject's head is within the critical distance in this test environment. Finally, signals (sentences and noise) were fed from a Macintosh-driven digital audio workstation, using MOTO AudioDesk software and a MOTU Model 828 8-channel FireWire A/D-D/A converter. The 0° loudspeaker was driven by an Alesis Model RA-150 amplifier in bridge-mono mode. Individual channels of Carvin DC-150 amplifiers drove the remaining loudspeakers.

To ensure that the overall presentation level was 65 dBA for the two loudspeaker and noise type conditions, a 1/2" microphone connected to a Quest 1900 precision sound level meter and OB-300 1/3-1/1 octave band filter was placed at ear level, with the subject absent, one meter from the loudspeakers. Because the noise from each loudspeaker was uncorrelated to each other in the diffuse condition, the output level of each loudspeaker can be easily adjusted to yield the same overall output for each test-loudspeaker condition. For the 180° condition, the overall level of the 180° loudspeaker was 65 dBA. Calibration of this single loudspeaker was completed

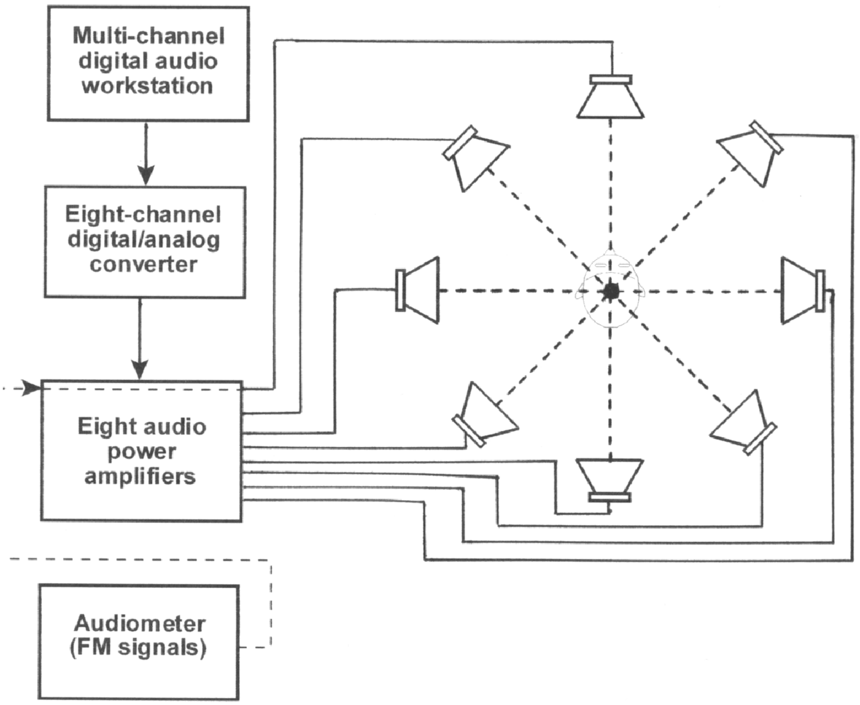

Figure 3. Illustration of the signal delivery and loudspeaker array used in the present study. For the 180° noise condition, only the rear loudspeaker was active. For the diffuse condition, the noise was delivered from all eight loudspeakers. For both loudspeaker conditions, the HINT sentences were delivered from the loudspeaker at 0° azimuth.

weekly, and the measured output was within +/-1 dB of 65 dBA throughout the course of the study. For the diffuse condition, the overall output from each loudspeaker was 56 dBA (10 $\log_{10}[8]$ where "8" denotes the number of loudspeakers or 9 dB). Thus, 65 dBA - 9 dBA = 56 dBA at each loudspeaker, so when summed, the output from the eight loudspeakers at one meter was 65 dBA. Calibration of each loudspeaker was completed weekly, and the measured output was within +/-1 dB of 56 dBA throughout the course of the study. Calibration of the summed loudspeakers was also completed weekly, and the measured output was within +/-1 dB of 65 dBA throughout the course of the study

The purpose for using this continuous noise rather than the gated noise provided by the HINT recording was that the noise approximates more closely real-world noisy situations. Finally, a lavaliere microphone was placed near the subject's mouth so the examiner could hear the subject's response to the HINT sentences.

RESULTS AND DISCUSSION

Main Effects of Microphone, Loudspeaker Array, and Noise Type

Figure 4 reports the mean RTS (in dB) for the microphone (omnidirectional, directional, benefit), loudspeaker array (180°, diffuse), and noise type (R-Space restaurant noise, HINT) conditions. An RTS of 0 dB means the subject required the intensity level of the sentences to be equal to the level of the noise (65 dBA) in order to correctly repeat back 50% of the sentences. Thus, a higher RTS reflects poorer performance, and a lower RTS reflects better performance. Table 1 reports the mean, standard deviation (SD), standard error, and the upper and lower bounds of the 95% confidence interval (CI) for the eight experimental conditions.

A repeated randomized block ANOVA (Kirk, 1982) was performed on the data appearing in Table 1 and Figure 4. The ANOVA revealed significant main effects for microphone ($F = 168.14$; $df = 1,24$; $p < 0.0001$), loudspeaker ($F = 18.51$; df = 1,24; $p < 0.0001$), and noise ($F = 49.06$; df = 1,24; $p < 0.0001$). In addition, the ANOVA revealed a significant microphone by loudspeaker interaction ($F = 15.71$; df = 1,24; $p < 0.001$). The noise by loudspeaker ($F = .586$; df = 1,24; $p < 0.451$), noise by microphone ($F = 1.13$; df = 1,24; $p < 0.298$) two-factor interactions and noise by microphone by loudspeaker ($F = 1.17$; df = 1,24; $p < 0.291$) three-factor interaction were not significant.

Figure 4 reports that the mean RTS for omnidirectional performance, averaged across loudspeaker and noise type conditions (0.98 dB), was significantly poorer than the mean RTS for directional performance (-2.30 dB or a mean directional benefit of 3.28 dB). Thus, assuming a 8.9%/dB improvement in sentence intelligibility of the HINT sentences (Soli and Nilsson, 1997), the overall directional benefit could be as much as approximately 29%. The observed power was 1.0 based on a computed alpha of .05, indicating that the sample size was sufficient for the reported effect size of 3.28 dB.

Figure 4 also reports that the mean RTS for the 180° condition, averaged across microphone and noise type conditions (-1.27 dB), was significantly better than the mean RTS for the diffuse condition (-0.05 dB or a mean difference of 1.22 dB). This 1.2 dB difference would suggest that a user could achieve, on average, as much as approximately 11% improvement in sentence recognition when there is a single noise source from behind relative to when the user is communicating in an environment where the noise was more diffuse. The computed observed power was 0.99 based on a computed alpha of .05 indicating that the sample size was sufficient for the reported effect size of 1.22 dB.

Finally, Figure 4 reports that the mean RTS for the HINT noise, averaged across microphone and loudspeaker conditions (-1.45 dB), was significantly better than the mean RTS for the R-Space restaurant noise (-0.15 dB or a mean difference of 1.30 dB). This 1.3 dB difference would suggest that a user could achieve, on average, as much as approximately 12% improvement in sentence recognition when listening in an environment where the characteristics of the noise is similar to the HINT noise source in comparison to when listening in an environment where the noise source has the characteristics of the R-Space restaurant noise. The computed observed power was 1.0 based on a computed alpha of .05, indicating that the sample size was sufficient for the reported effect size of 1.30 dB.

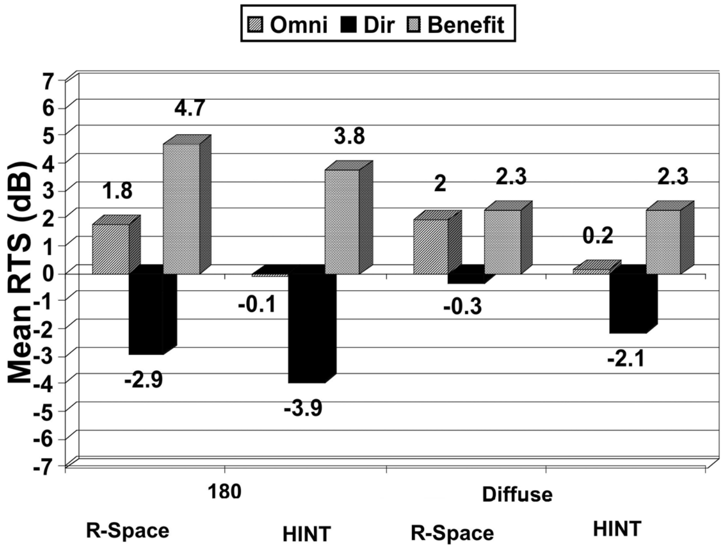

Figure 4. Mean RTS (in dB) for omnidirectional, directional, and benefit for the two noise types and two loudspeaker arrays.

Table 1. Mean RTS (dB), Standard Deviation, Standard Error, and the Lower and Upper Bounds of the 95% Confidence Interval (CI) for the Eight Experimental Conditions

Condition	Mean	SD	Standard Error	95% CI Lower	Upper
180°					
R-Space Omni	1.8	3.2	.64	.452	3.10
R-Space Directional	-2.9	2.9	.58	-4.12	-1.72
HINT Omni	-0.1	2.0	.41	-0.93	0.75
HINT Directional	-3.9	2.9	.59	-5.08	2.65
Diffuse					
R-Space Omni	2.0	2.6	.52	0.94	3.11
R-Space Directional	-0.3	2.3	.46	-1.24	0.67
HINT Omni	0.2	2.0	.40	-0.61	1.06
HINT Directional	-2.1	2.6	.52	-3.16	-1.00

Microphones *within* Loudspeaker Interaction

As mentioned earlier, the ANOVA revealed a significant microphone by loudspeaker interaction. Post hoc analysis using the Pillai's Trace Test ($F = 101.3$; $p < 0.0001$) revealed that the mean RTS for the omnidirectional (0.85 dB) condition was significantly poorer than the mean RTS for the directional condition (-3.4 dB or a mean difference of 4.25 dB) for the 180° condition. In addition, post hoc analysis using the Pillai's Trace Test ($F = 77.45$; $p < 0.0001$) revealed that the mean RTS for the omnidirectional (1.1 dB) was significantly poorer than the mean RTS for the directional condition (-1.2 dB or a mean difference of 2.3 dB) for the diffuse condition. That is, for both listening environments, directional performance was significantly better than omnidirectional performance. Moreover, the magnitude of the improvement provided by the directional microphone decreased as the difficulty of the listening environment increased (4.3 dB directional advantage for 180°; 2.3 dB directional advantage for diffuse). Thus, assuming an 8.9%/dB improvement in sentence intelligibility of the HINT sentences (Soli and Nilsson, 1997), the directional microphone improved performance in noise, with regard to omnidirectional performance, by 20 to 38%. The computed observed power was 1.0 based upon a computed alpha of .05 indicating that the sample size was sufficient for the reported effect sizes of 4.3 and 2.3 dB.

Microphones *between* Loudspeaker Interaction

Post hoc analysis using the Pillai's Trace Test ($F = 0.5$; $p < .48$) revealed that the mean RTS for the omnidirectional performance for the 180° condition (0.85 dB) was not significantly different from the mean omnidirectional performance (1.12 dB or a mean difference of 0.27 dB) for the diffuse condition. That is, performance with an omnidirectional microphone was similar as the difficulty in the listening environment increased. On the other hand, post hoc analysis using the Pillai's Trace Test ($F = 35.99$; $p < .48$) revealed that the mean RTS for directional performance for the 180° condition (-3.4 dB) was significantly better than directional performance (-1.2 dB or a mean difference of 2.2 dB) for the diffuse condition. That is, unlike the lack of performance differences in omnidirectional performance as the listening environment became more difficult, the performance with the directional microphone became poorer as the listening environment became increasingly more difficult. The authors believe it is realistic to expect directional performance to vary based on the complexity of the listening environment and that this information needs to be conveyed to patients as part of the counseling process. Suggestions on how this information may be included in patient counseling is presented in the paragraphs that follow. Finally, the computed observed power was 1.0 based on a computed alpha of .05 indicating that the sample size was sufficient for the reported effect sizes of 2.2 dB.

Comparison with Studies Using a Single Loudspeaker at 180°

There has been an abundance of papers published since the 1980s on assessing directional microphone performance. It is beyond the scope of this study to review all these findings. If interested, the reader may wish to read the excellent manuscript by Amlani (2001), who provides a meta-analytic perspective of numerous investigations on this topic. For the purposes of this discussion, only a few investigations appearing to be representative of the general findings on this issue will be presented.

With a loudspeaker at 180°, Ricketts (2000b) reported a mean directional benefit in RTS for hearing aids from three manufacturers between 5.1 to 7.8 dB, while the current study reported a mean directional benefit of 3.8 to 4.7 dB for the same loudspeaker array depending on the type of noise. As with any study, there may be significant differences in methodology that may help to explain the reported differences between studies. In the case of the Ricketts (2000b) study, the participants exhibited greater hearing loss at 250–2000 Hz than the participants of the current study. The impact of hearing loss on microphone performance is mixed. Killion and Christensen (1998) report decreased performance as hearing loss increased, but several studies report little or no impact of hearing loss (Ricketts and Mueller, 2000; Kuhnel et al, 2001; Kuk et al, 2004) on microphone performance. Second, the directional benefit reported by Ricketts (2000b) represents the average across hearings aids (Phonak Piconet, Siemens Prisma, and Widex Senso) whose signal processing is significantly different than the hearing aid used in the current study. Finally, Ricketts (2000b) used cafeteria noise, while the current study used HINT and R-Space restaurant noise, and the possible impact of this variable will be discussed later. Other variables might include venting and the dimensions of the room in which testing was performed. For example, the data by Ricketts (2000b) was obtained in rooms considerably larger than the internal dimensions of the test suite used in the current study. Nilsson et al (2005) reported significantly improved directional performance in a larger room with poorer performance as room size decreased. In addition, Ricketts (2000b) used earmolds with a 1 mm pressure vent, while, as reported earlier, the current study used vent diameters greater than 1 mm for 84% of the ears. Kuk et al (2004) reported reduced directional performance as vent diameter increased.

In the Amlani (2001) meta-analysis, he reports a range of directional benefit for 11 studies using a single loudspeaker at 180° and minimal reverberation of between 3.0 (Schum, 1990) to 16.4 dB (Dybala, 1996) depending on the hearing sensitivity of the subject (normal or hearing impaired and magnitude of hearing loss) and type of signal (words or sentences and noise [steady state, babble, cocktail, or cafeteria]). With increased reverberation, the directional benefit decreased to be between -0.6 (Hawkins and Yacullo, 1984) and 8.0 dB (Dybala, 1996) depending on these same variables.

Comparison with Studies Using Multiple Loudspeakers with Loudspeakers in Front

Considerably fewer papers have been published on assessing directional microphone performance using a diffuse array that included at least one loudspeaker in the front of the subject and uncorrelated noise. This section of the discussion will highlight some of those studies and how the results compared with the results reported in the current study.

In the same study described above, Ricketts (2000b) used a five loudspeaker array to surround the participants with cafeteria noise. These loudspeakers were behind and in front of the subject (5/S where loudspeakers were at 30, 105, 180, 255, and 330° and m5/S which was the same as 5/S, but the 30 and 330° loudspeakers were turned to face perpendicular to the subject). Using these arrays, Ricketts (2000b) reported a mean directional benefit in RTS for hearing aids from three manufacturers between 2.0 and 4.9 dB, while the current study reported a mean directional benefit of 2.3 dB for both types of noise under the diffuse condition. In addition to the differences between these two studies noted earlier, the current study had noise delivered from all eight (including the same loudspeaker emitting the signal at 0°), whereas in the Ricketts (2000b) study noise was not delivered from the front loudspeaker.

It is hypothesized that delivering uncorrelated noise from directly in front as well as at 45 and 315° resulted in a more difficult listening environment, and this may help explain the poorer mean directional benefit in the current study than that reported by Ricketts (2000b).

In another study, Ricketts et al (2001) and his colleagues evaluated directional performance in a moderately reverberant room using ITE and BTE hearing aids with varying compression characteristics. Sentence recognition was evaluated using HINT sentences at 0° and uncorrelated cafeteria noise, presented at 65 dBA delivered from loudspeakers at 30, 105, 180, 225, and 330° with noise reduced by 5 dB in the two loudspeakers facing the participants (30 and 330°). Results, depending on model, were reported to be a mean directional benefit of 2.2 to 2.9 dB. These results are very close to the 2.3 dB directional benefit reported here.

In a study by Bentler et al (2004), she and her colleagues evaluated 19 participants using an analog directional custom hearing aid evaluated in an anechoic chamber. For this study, a diffuse sound field of eight loudspeakers "forming the corners of a cube" (i.e., loudspeakers in each of the upper and lower corners of the anechoic chamber facing the subject and a ninth loudspeaker at 0° emitting the sentence material) was utilized. Five microphone conditions were evaluated: omnidirectional, cardioid, hypercardioid, supercardioid, and monofit, where the left hearing aid was omnidirectional and the right hearing aid was hypercardioid. HINT testing was used to measure sentence recognition where the HINT noise was held constant at 65 dBA. Results, pertinent to this study, revealed an average directional advantage of 2.5 dB equal across the four directional conditions. Again, this finding is in close agreement with the 2.3 dB reported here. Pumford et al (2000), using loudspeakers at 72, 144, 216, and 288°, reported no significant difference in directional performance between ITE and BTE models but reported a directional benefit (directional-omnidirectional performance) of 3.3 dB for the ITE model and 5.8 dB for the BTE model due to the poorer omnidirectional performance of the BTE. Although not investigated in this study, Ricketts et al (2001) evaluated directional performance using ITE and BTE hearing aids and reported a mean directional benefit of 2.2 to 2.9 dB with no significant differences between models. Finally, Larsen (1998) reported a 3.6 dB directional benefit with loudspeakers at 45, 135, 225, and 315°.

R-Space Restaurant Noise

In the only study that has reported using the R-Space restaurant noise, Compton-Conley et al (2004) reported a mean directional benefit of 3.6 dB in a hearing device using a supercardioid polar design to 5.8 dB with a device using a hypercardioid polar design while the results of the current study report a mean directional benefit RTS of 2.3 dB. In this study, Compton-Conley et al (2004) reported (Figure 4, page 447) that the long-term speech spectra of the HINT sentences, HINT noise, and R-Space noise was very similar between approximately 500 to 8000 Hz. It is important to note that the Compton-Conley et al (2004) study was based on a smaller subject sample (N = 12), normal-hearing listeners, and hearing aids that differed significantly from the hearing aids used in the current study.

One final thought: Although the R-Space simulation holds promise to provide results having greater external validity than has been present in the past, it must be remembered that the noise recording used in the R-Space simulation is unique to the restaurant in which the recording was made. It would be naïve to assume that the results measured in the clinic/laboratory using this simulation would be applicable to all restaurant or noisy environments. It would be beneficial to clinicians/researchers if a "library" of common environments (house of worship, cab, airplane, office, etc.) were recorded/simulated and could be selected from a computer software program to introduce into the multi-loudspeaker sound field within the clinic. Even better, it would be interesting if a system could be developed where a patient could place small microphones in their ears and record the environments (communication with a spouse in the home, watching television, meeting room, house of worship, office, classroom, car, radio, living room, etc.) most important to him or her and then play these samples back on a playback unit within a clinic to provide for more custom hearing aid fittings.

Impact of Type of Noise

As mentioned earlier, there has been only one published study in a peer-reviewed paper on the R-Space restaurant noise. The results of the current study found that the mean RTS for the HINT noise (-1.45 dB) was significantly better than the mean RTS for the R-Space restaurant noise (-0.15 dB or a mean difference of 1.30 dB) averaged across microphone and loudspeaker conditions. In a report by Nilsson et al (2005), he and his colleagues compared RTS using HINT noise and multitalker babble (1 to 16 talkers). Testing was completed in a sound field where the loudspeakers delivering the noise at 0 (noise-front or NF) or at 45, 135, 225, and 315°. HINT sentences were delivered at 0°. Both signal and noise(s) were at one meter, and the level of the noise(s) was 65 dBA. Results revealed a mean 2.5 dB improvement in RTS when the HINT noise was spatially separated (uncorrelated HINT noise from the four loudspeakers) than when the same noise was from the same loudspeaker as the sentences (NF). This finding agrees with past research that reports improved performance as the competing noise is spatially separated from the target signal. More importantly, Nilsson et al report that the mean RTS decreased from -5.4 dB (uncorrelated HINT noise from the four loudspeakers) to 2.1 dB for the 16 multitalker babble condition. That is, performance was poorer for the multitalker condition than for the continuous HINT noise condition, and the difference increased from 0.7 dB for the 4-talker babble to 3.3 dB for the 16-talker babble. The authors theorize that the presence of fewer talkers may allow the listener to take advantage of *temporal gaps* in the masker to allow him or her to pick out the target signal, and that as the number of talkers increases, the number of temporal gaps decreases, thus resulting in poorer performance. The finding from the Nilsson et al (2005) study is in agreement with the results from the current study where mean performance was poorer for the restaurant noise than the HINT noise.

Implications for Patient Counseling

The authors believe these results could be used by manufacturers to change the information conveyed to audiologists concerning performance of directional microphones. That is, one purpose of the study was to deliver noise under an "optimum" condition (i.e., single loudspeaker behind the listener, constant noise source, noise matched the speech spectrum) as well as an "extremely difficult" condition (i.e., diffuse noise surrounding the listener, using a more distracting noise source that has been reported to have excellent external validity) in an attempt to obtain a better understanding of the potential *range of directional benefit*. By way of comparison, when consumers purchase automobiles, they are informed to expect "x" miles/gallon in fuel efficiency that varies between "x" and "x" miles/gallon depending on if driving is in the city or on the highway. This information, often, is used by consumers when purchasing a car. Along the same lines, manufacturers might consider reporting the *range* of predicted directional benefit or performance based on whether communication is in an "optimal" or "very difficult listening environment." For example, if the results from this study were used, manufacturers could report it is expected that, on average, a user may expect a directional benefit of 2.3 to 4.7 dB depending on if it is an "optimal" or "very difficult" listening environment. This could translate to an improvement of 20 to 42% with regard to listening with an omnidirectional microphone. Of course, the audiologist will need to counsel on how individual performance might vary due to a wide variety of factors (i.e., reverberation; type, direction[s], and intensity of the noise; dimensions of the room; talker gender; listener knowledge of the content of the speech signal; etc.).

The results from the current study could be used to enhance patient counseling on realistic expectations from hearing aids in general and directional microphones specifically. As is generally known, communication in a noisy restaurant is a common complaint of many hearing aid users. Let us assume that the typical listener will communicate in a restaurant having noise characteristics similar to the R-Space. In looking at Figure 4, the participants reported a directional benefit of 4.7 dB when this noise was directly behind, and this benefit decreased to 2.3 dB when the noise surrounded the listener. That is, the directional benefit decreased by 2.4 dB, revealing almost half the benefit in the more diffuse environment relative to when the same noise source was only behind. The fact remains, however, that under no tested condition was performance better using the omnidirectional microphone. Thus, the results from this study could be explained to the patient in the following manner. First, expect performance in a noisy restaurant to be better with a directional microphone than with an omnidirectional microphone. Second, the magnitude of the benefit will be about half when the noise completely surrounds the patient than when the noise is simply directly behind. Finally, the results of the present study could be integrated into patient counseling, not from the results of this study but, rather, from clinical observations of the first author. It appears to be common for patients purchasing "new" hearing aids to *expect* to hear as well as their normal-hearing friends in a noisy restaurant. To directly address this expectation, the first author asks the patient, when communicating in noisy situations, to mentally "score" the percent of the conversation he or she has understood from his or her "normal" hearing friend(s). Next, the patient then asks his normal-hearing friend(s) what percent of *the patient's conversation* the friend understood. It has been the experience of the first author that very often the difference between these two "scores" is not as great as the patient previously predicted they might be. That is, the patient now has a greater appreciation that even friends with normal hearing experience significant difficulty in noisy environments. After completing this simple exercise, the patient typically has a better "feel" for the benefit achieved with his or her aids, and his or her expectations are more realistic. Moreover, audiologists should counsel that even greater benefit in noise can be achieved with hearing assistive technology (HAT) (Lewis et al, 2004) and auditory rehabilitation.

CONCLUSIONS

The major findings of this study revealed:

1. The mean RTS for omnidirectional performance (0.98 dB) was significantly poorer than the mean RTS for directional performance (-2.30 dB or a mean benefit of 3.28 dB) averaged across loudspeaker and noise type conditions.
2. The mean RTS for the 180° condition (-1.27 dB) was significantly better than the mean RTS for the diffuse condition (-0.05 dB or a mean difference of 1.22 dB) averaged across microphone and noise type conditions.
3. The mean RTS for the HINT noise (-1.45 dB) was significantly better than the mean RTS for the R-Space noise (-0.15 dB or a mean difference of 1.30 dB) averaged across microphone and loudspeaker conditions.
4. The mean RTS for the omnidirectional (0.85 dB) condition was significantly poorer than the mean RTS for the directional condition (-3.4 dB or a mean difference of 4.25 dB) for the 180° condition. In addition, the mean RTS for the omnidirectional (1.1 dB) was significantly poorer than the mean RTS for the directional condition (-1.2 dB or a mean difference of 2.3 dB) for the diffuse condition. That is, for both listening environments, directional performance was significantly better than omnidirectional performance. Moreover, the magnitude of the improvement provided by the directional microphone decreased as the difficulty of the listening environment increased (4.25 dB directional advantage for 180°; 2.3 dB directional advantage for diffuse).
5. The mean RTS for the omnidirectional performance for the 180° condition (0.85 dB) was not significantly different from the mean omnidirectional performance (1.12 dB or a mean difference of 0.27 dB) for the diffuse condition. On the other hand, the mean RTS for directional performance for the 180° condition (-3.4 dB) was significantly better than directional performance (-1.2 dB or a mean difference of 2.2 dB) for the diffuse condition.
6. These results were discussed in ways to improve patient counseling and compared to results reported in the past using similar loudspeaker arrangements.

Acknowledgments. We thank Phonak for providing a small grant to cover the direct costs involved for completing the project and allowing the participants to purchase the experimental hearing aids at a significantly reduced cost at the conclusion of the study. The authors thank Michael Strubbe, Ph.D., Professor of Psychology at Washington University, for his help in completing the statistical analysis and appropriate interpretation of the data reported in this manuscript. We thank three anonymous reviewers for their comments and suggestions. Those efforts significantly improved the quality of this paper. Finally, we thank Larry Revit and Michael Nilsson for their assistance in addressing some of the suggestions of the reviewers.

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