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Predicting Hearing Aid Microphone Preference in Everyday Listening

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Abstract

Seventeen hearing-impaired adults were fit with omnidirectional/directional hearing aids, which they wore during a four-week trial. For each listening situation encountered in daily living during a total of seven days, participants selected the preferred microphone mode and described the listening situation in terms of five environmental variables, using a paper and pencil form. Results indicated that hearing-impaired adults typically spend the majority of their active listening time in situations with background noise present and surrounding the listener, and the signal source located in front and relatively near. Microphone preferences were fairly evenly distributed across listening situations but differed depending on the characteristics of the listening environment. The omnidirectional mode tended to be preferred in relatively quiet listening situations or, in the presence of background noise, when the signal source was relatively far away. The directional mode tended to be preferred when background noise was present and the signal source was located in front of and relatively near the listener. Results suggest that knowing only signal location and distance and whether background noise is present or absent, omnidirectional/directional hearing aids can be set in the preferred mode in most everyday listening situations. These findings have relevance for counseling patients when to set manually switchable omnidirectional/directional hearing aids in each microphone mode, as well as for the development of automatic algorithms for selecting omnidirectional versus directional microphone processing.

Key Words: Directional microphones, everyday listening situations, hearing aids

Abbreviations: AASC = Army Audiology and Speech Center; BN = background noise; BTE = behind the ear; DA = directional advantage; DIR = directional; DFS = digital feedback suppression; HAUL = Hearing Aid Use Log; HINT = Hearing in Noise Test; ITE = in the ear; OMNI = omnidirectional; PLS = prototype listening situation; RTS = reception threshold for sentences; SNR = signal-to-noise ratio; WDRC = wide dynamic range compression

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Sumario

Se adaptaron auxiliares auditivos direccionales/omnidireccionales a diecisiete adultos hipoacúsicos, quienes los utilizaron durante un período de cuatro semanas. Para cada situación auditiva en la vida diaria durante un total de siete días, los participantes seleccionaron la escogencia preferida de micrófono y describieron tal situacion auditiva en términos de variables ambientales, utilizando una fórmula para llenar con lápiz. Los resultados indicaron que los adultos hipoacúsicos pasaron la mayor parte de su tiempo activo de audición en situaciones con ruido de fondo presente y rodeando el sujeto, y con la fuente de estímulo ubicada al frente y relativamente cerca. Las preferencias de micrófono se distribuyeron uniformemente en todas las situaciones auditivas, pero difirieron dependiendo de las características de los ambientes de escucha. Se prefirió el modo omnidireccional en situaciones auditivas de relativa quietud o en presencia de ruido de fondo, cuando la fuente de estímulo estaba relativamente lejana. Se prefirió el modo direccional cuando había ruido de fondo presente y la fuente de estímulo se localizaba al frente y relativamente cerca del sujeto. Los resultados sugieren que conociendo solamente la localización y la distancia de la señal, y si existe o no ruido de fondo presente, se pueden programar los micrófonos omnidireccionales/direccionales en el modo preferido, para la mayor cantidad de situaciones auditivas cotidianas. Estos hallazgos tienen relevancia para aconsejar a los pacientes usando auxiliares auditivos omnidireccionales/direccionales con interruptores manuales, sobre cuándo activar cada modalidad de micrófono, al igual que para el desarrollo de algoritmos automáticos que seleccionen el procesamiento del micrófono omnidireccional versus el direccional.

Palabras Clave: Micrófonos direccionales, situaciones auditivas cotidianas, auxiliares auditivos

Abreviaturas: AASC = Centro de Audición y Lenguaje del Ejército; BN = ruido de fondo; BTE = retroauricular; DA = ventaja direccional; DIR = direccional; DFS = supresión digital de la retroalimentación; HAUI = bitácora de uso del auxiliar auditivo; HINT = Prueba de audición en ruido; ITE = intraauricular; OMNI = omnidireccional; PLS = situación auditiva prototipo; RTS = Umbral de recepción de frases; SNR = tasa de relación señal/ruido; WDRC = compresión de rango dinámico amplio

Studies conducted in audiometric test suites have shown significant improvement in aided speech recognition in noise with directional microphones in comparison to omnidirectional microphones (Valente et al, 1995; Ricketts and Dahr, 1999). This difference between the two microphone modes is referred to as the directional benefit or advantage. Although benefit from directional microphones has been documented in everyday listening as well (Killion et al, 1998; Preves et al, 1999; Kochkin, 2000), some studies suggest that directional advantages comparable to those observed in controlled clinical test environments are not observed in listening environments typically encountered in daily living (Nielsen and Ludvigsen, 1978; Valente et al, 1995). This discrepancy between test booth and field data may be because test booth measures tend to overestimate the directional advantage that will actually be obtained in everyday listening (Amlani, 2001). The specific test conditions typically used in the test booth involve the signal being presented from the front and the noise from the sides and/or back of the listener. Such conditions should favor directional microphones. Laboratory studies have shown that directional benefit is influenced by the amount of spatial separation between signal and noise sources, the distance between the signal source and the listener, and the amount of reverberation introduced (Leeuw and Dreschler, 1991; Ricketts, 2000). As the environmental conditions encountered in everyday listening deviate from relatively ideal laboratory conditions, the directional advantage is diminished (Studebaker et al, 1980; Madison and Hawkins, 1983; Hawkins and Yacullo, 1984).

Walden et al (2000) conducted a clinical trial of a digital hearing aid with the omnidirectional/directional option that illustrated the disparity between test booth and field data. Test booth speech recognition scores in noise showed highly significant directional advantages, but subjective ratings in daily use showed minimal directional benefit. Walden et al suggested a number of possible explanations for the discrepancy between directional microphone benefit observed in an audiometric suite and in everyday use, including the likelihood that most real-life listening situations may not closely match the acoustics of the test booth.

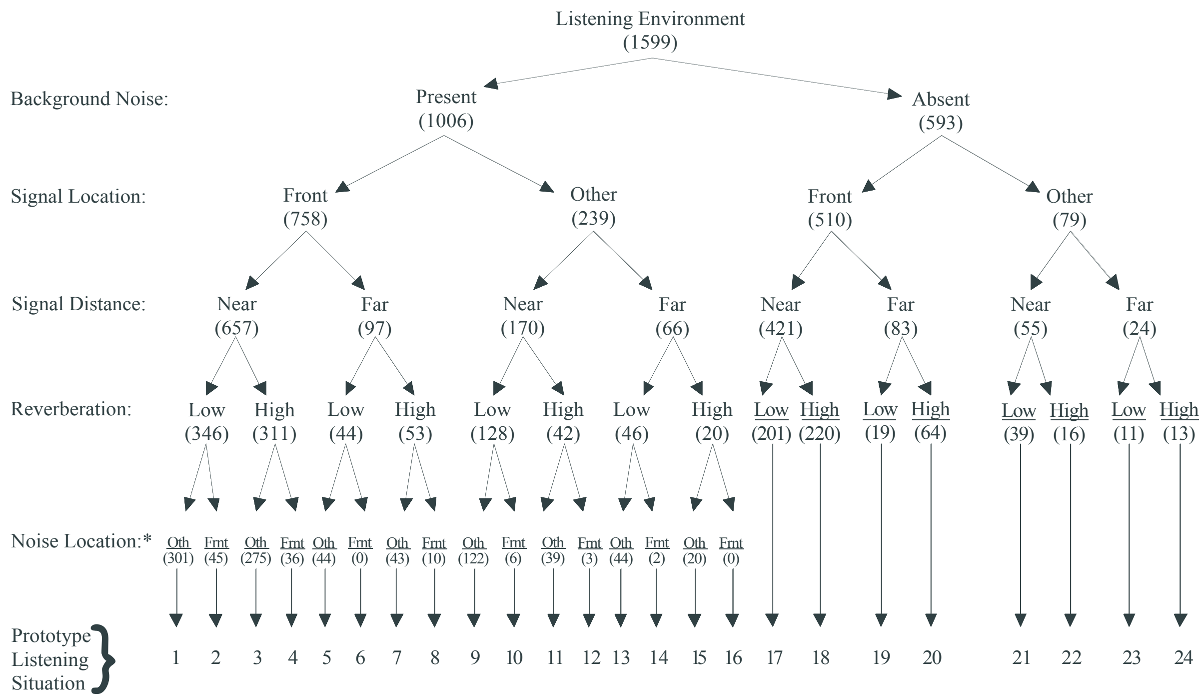
Although a variety of factors may contribute to a directional advantage, it appears that the benefit obtained from either microphone type is particularly dependent on the physical characteristics of the listening environment. From this perspective, only when a specific set of environmental conditions exists in everyday listening will one or the other microphone mode provide superior performance.

Two recent studies (Cord et al, 2002; Surr et al, 2002) were designed to explore issues surrounding the use of dual-microphone hearing aids in everyday listening. Cord et al explored the benefits of directional microphone technology in real-world situations experienced by successful users of switchable omnidirectional/directional hearing aids. Telephone interviews and paper-and-pencil questionnaires were used to assess perceived performance with each microphone mode. The results suggested that the benefit of directional microphones in everyday listening is highly dependent on the specific characteristics of the listening situations encountered. Participants perceived that the directional microphone mode was superior to the omnidirectional microphone mode with background noise present; the signal source located in front of the listener and spatially separated from the source of the background noise; low reverberation; and the talker close to the listener. In Surr et al, 11 experienced hearing aid users were fit with digital hearing aids featuring switchable omnidirectional and adaptive-directional modes. For six weeks, their task was to identify and describe at least one listening situation each day in which one microphone mode performed better than the other using a checklist daily journal format. Although all participants reported difficulty in identifying situations where they perceived a difference between the two microphone modes, descriptions favoring the directional mode outnumbered those for the omnidirectional mode. The results indicated that location of the primary talker, presence or absence and type of background noise, and type of space in which the communication occurred influenced microphone preference.

Taken together, the Cord et al (2002) and Surr et al (2002) studies suggest that the following characteristics of a listening environment serve as major determinants in success with either omnidirectional or directional hearing aid microphones: (a) presence/absence of background noise, (b) location of the signal source, (c) distance of the listener from the signal source, (d) amount of reverberation present, and (e) location of the noise source in relation to the signal source. Neither study definitively determined how often participants could tell a difference between the microphone modes in everyday listening situations, or how frequently specific situations favoring one mode or the other were encountered. However, results from Cord et al suggested that situations favoring the omnidirectional mode might occur significantly more frequently in everyday life than situations favoring the directional mode.

The study reported here was intended to determine the extent to which the preferences of hearing-impaired patients for the omnidirectional versus the directional mode in everyday listening situations could be predicted from the characteristics of the listening environments. Participants were asked to describe the listening environments that they encountered in everyday living, and to give a microphone preference for each listening situation encountered. In addition, participants described how long they were in each listening situation and whether they considered it to be easy or difficult. The following questions were addressed:

1. What are the characteristics of everyday listening situations typically encountered by hearing-impaired adults?
2. How often in everyday living are listening situations encountered in which there is a distinct preference for the omnidirectional mode or for the directional mode?
3. To what extent can microphone preferences be predicted from the characteristics of the listening environment?



*Oth=Noise from back, sides, diffuse
Frnt=Noise from in front of listener

Figure 1. Model defining 24 prototype listening situations based on binary representations of five environmental variables. The numbers in parentheses are discussed later.

METHOD

The Model

These questions require that everyday listening situations be characterized in a way that permits description and analysis. Clearly, listening situations encountered in daily living can vary in virtually an infinite variety of ways. The model depicted in Figure 1 was used to categorize everyday listening environments according to binary representations of five acoustic (i.e., signal and noise) characteristics (left column), resulting in 24 unique categories or "prototype listening situations" (PLS). The order in which the five variables are represented in the model (from top to bottom) is relatively arbitrary. The model takes the input signal (e.g., a talker located in the environment) and successively adds binary variables, resulting in row 1 (background noise) having two conditions, row 2 (signal location) having four conditions, row 3 (signal distance) having eight conditions, and row 4 (reverberation) having 16 conditions. Row 5 (noise location) has only 16 conditions, as well, because there is no noise location when background noise is absent from the environment. The resulting 24 "paths" from the top to the bottom of the model describe 24 different general types of listening situations (i.e., 24 different combinations of the five environmental variables). Although it may be argued that no two listening situations encountered in everyday living are exactly alike, for the purposes of this study it is assumed that the range of everyday listening situations encountered by hearing-impaired adults is meaningfully categorized into these 24 PLS. The numbers in parentheses in Figure 1 will be discussed later.

Based on earlier behavioral studies (Walden et al, 2000; Cord et al, 2002; Surr et al, 2002), the five environmental variables included in the model appeared to influence microphone performance in everyday listening situations. This view is consistent with the purpose and operation of directional microphones (see, for example, Ricketts, 2001). *Other things being equal*, the directional mode should be preferred when background noise is present, and the omnidirectional mode should be preferred in quiet, or at least there should not be a strong preference for the directional mode in quiet. Similarly, the directional mode should be preferred when the signal source is located in front of the listener,

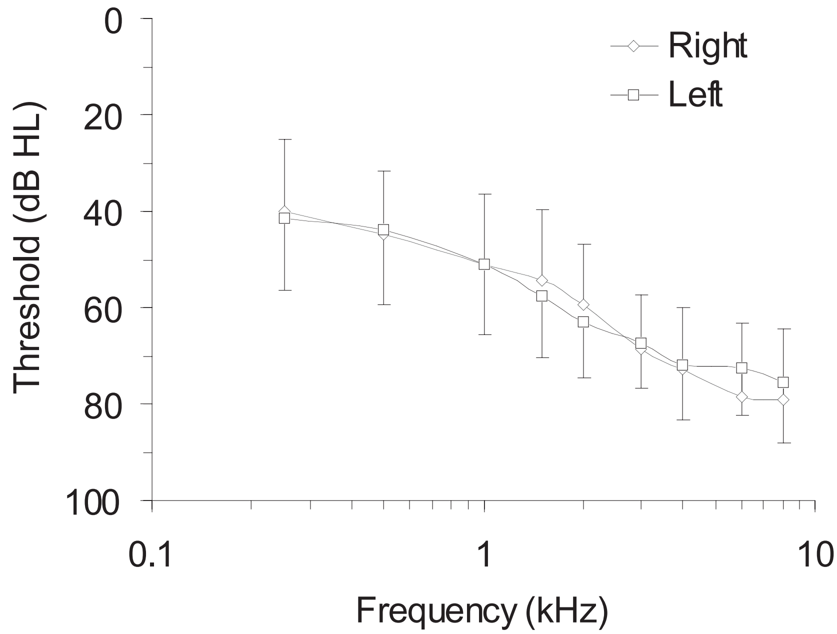


Figure 2. Mean audiometric data for the 17 participants. The error bars indicate one standard deviation.

when the signal source is located near to the listener, when reverberation is low, and when the noise source is located other than in front of the listener. Conversely, the omnidirectional mode should be preferred (or there should not be a strong preference for the directional mode) when the signal source is located other than in front of the listener, when the signal source is located far from the listener, when reverberation is high, and when the noise source is located in front of the listener.

Although these predictions may apply "other things being equal" (i.e., in a theoretical sense), the influence of each of these environmental variables does not occur in isolation from the influences of each of the other variables. Rather, they coexist with each other to define the acoustic environment. Consequently, even if the assumed influence described above is correct for each environmental variable considered independently, it is not immediately apparent which of the two microphone modes will be preferred in a listening situation where the assumptions lead to contradictory predictions. Thus, for example, it is not self-evident which microphone mode would be preferred in a listening situation with background noise present (predicts directional mode) and the signal at a distance (predicts omnidirectional mode). For such listening situations, the preferred microphone mode must be determined empirically. The primary purpose of this study is to describe microphone preferences (omnidirectional, directional, no difference) for each of the 24 PLS in order to determine if such preferences can be predicted from the acoustic characteristics of the listening environment.

Participants

Participants were 17 adults with impaired hearing who were fit with switchable omnidirectional/directional hearing aids at the Army Audiology and Speech Center (AASC) at least three months and not more than 72 months preceding enrollment. Although no participant was excluded on the basis of gender, 16 of the participants were male, reflecting the demographics of the AASC's hearing-impaired population. Their mean age was 70.8 years (SD = 9.6; range = 47–81). The mean years of hearing aid use prior to enrollment was 13.6 years (SD = 9.1; range = 2–33).

Participants had bilateral, symmetric sensorineural hearing impairments that fell within the fitting guidelines of the hearing aid used in the study. Sensorineural hearing loss (cochlear site of lesion) was verified by differences between air- and bone-conduction thresholds of 10 dB or less, by normal tympanograms (Type A; Jerger classification, 1970), and by the presence of ipsilateral acoustic reflexes for a 1000 Hz tone. Unaided monosyllabic word-recognition ability in quiet (NU-6) was 50% or better in each ear at a comfortable listening level. The mean audiogram for the 17 participants is shown in Figure 2. On average, participants had moderate-to-severe, gradually sloping, bilaterally symmetrical, sensorineural hearing loss. Mean word-recognition ability (NU-6) in quiet at a comfortable listening level was 81.1% (SD: 10.9; range: 64–96) for the right ears and 76.1% (SD: 14.5; range: 52–100) for the left ears.

Participants had to be successful users of switchable omnidirectional/directional hearing aids at the time of enrollment. Specifically, they had to report using their own hearing aids at least four hours per day and each microphone mode (omnidirectional, directional) a minimum of 10% of the time. Further, they had to affirm that the directional microphone option had been a useful feature of their hearing aid. Potential participants were screened with a test of speech recognition in noise while wearing the behind-the-ear version of the GN ReSound Canta7 to make sure that they obtained a directional advantage. This testing is described in more detail below.

Hearing Aids and Fitting Procedures

All participants were fitted with binaural GN ReSound Canta750D in-the-ear instruments using the Audiogram+ fitting algorithm of Aventa 1.2 software. The Canta7 is an open-platform digital, multiband, multimemory hearing aid with variable wide dynamic range compression (WDRC). The syllabic compression threshold is 40 to 48 dB SPL, and the compression ratio ranges from 1:1 to 3:1 (program dependent in each channel). The attack time is specified as 4 msec and release time as 80 msec. The instrument has no user-operated volume control. Directionality is achieved electronically via a two-microphone system and features an adaptive polar pattern option, as well as several fixed pattern choices. The adaptive option was used throughout this study. The first two memories were programmed with the manufacturer's "basic program" using the participant's hearing threshold data. The standard omnidirectional microphone mode was programmed into one of these two memories, and the directional mode was programmed into the other. These two programs will be hereafter designated as OMNI (omnidirectional) and DIR (directional). A push button on the faceplate of the instrument allowed the wearer to switch between programs. An appropriate number of audible tones informed the user whether program #1 or program #2 had been activated.

The frequency responses of the OMNI and the DIR were equalized (using the Max Bass Boost option in the fitting software) to

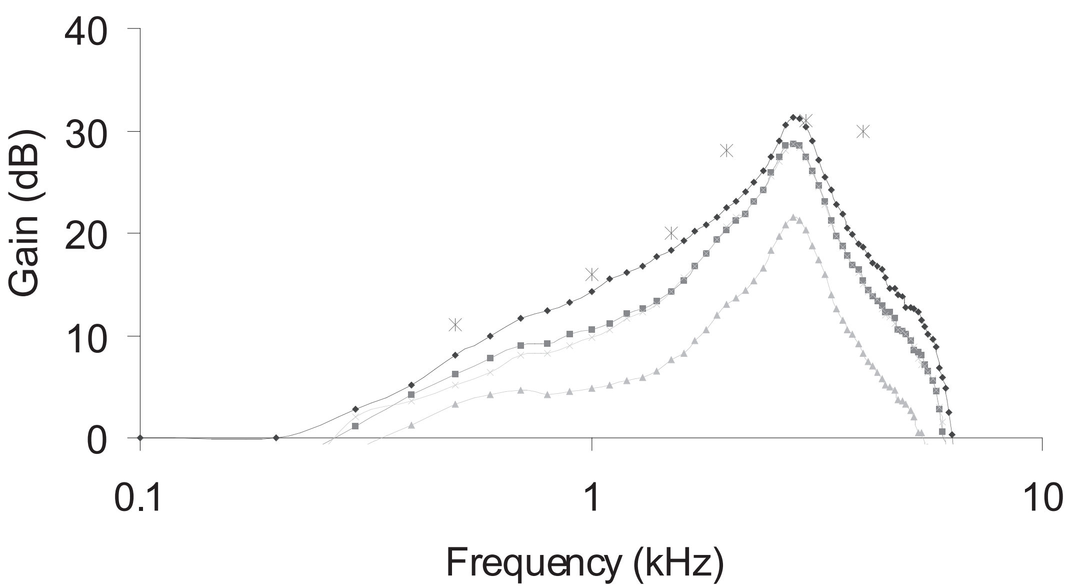


Figure 3. Mean 2-cc coupler gain of the test instrument averaged for the right and left ear fittings. The measurements were made in the omnidirectional mode using three input levels: 50 dB SPL (the top curve), 65 dB SPL (one of the middle curves), and 80 dB SPL (bottom curve). In addition, the measurements were made in directional mode with a 65 dB SPL input signal. The results intertwine with the corresponding omnidirectional line. Further, the DSL[i/o] target user-gain levels are shown by the symbols without a connecting line (see text for further explanation).

minimize the effect of the low-frequency roll-off typically associated with directional microphones. The digital feedback suppression (DFS) feature was activated for several participants as needed. Despite severe high-frequency hearing loss for many participants, prescribed high-frequency gain did not have to be reduced for anyone due to feedback problems. A digital noise reduction option, also available in these instruments, was not used in this study.

Two opportunities were available to make changes in the prescribed fitting parameters in response to the participant's subjective evaluation, at the time of the fitting and, again, after one-week use of the hearing aids. Manufacturer's guidelines for fine-tuning were employed. Changes to the prescribed fitting parameters were minor, if any, and relatively symmetric for the right and left fittings. Program adjustments were made while the participant listened in the OMNI mode, and they were extended to the DIR mode.

The hearing aids were tested in a Fonix 6500 test box with the front microphone opening closest to the reference circle. The mean frequency responses for the final fittings, averaged for the right and left hearing aids, for three input levels of speech-weighted noise (50, 65, and 80 dB SPL) are shown in Figure 3. These 2-cc coupler measurements were made in the OMNI mode and show the characteristic decrease in gain with increasing input level of WDRC circuits. This measurement was also obtained in the DIR mode with the 65 dB SPL input level (one of the middle lines overlapping the response curve for the corresponding curve for the OMNI mode) to examine the conformity of the frequency responses between the OMNI and the DIR, and thus to assure that the frequency-gain characteristics of the two programs were similar. The symbols without connecting lines show user gain for 65 dB input that were calculated using the Desired Sensation Levels (DSL[i/o] version 4.0) for the average audiogram of the participants for an ITE (in-the-ear) instrument with WDRC circuit and variable compression ratios.

Overview of Study Design

This study investigated microphone mode preferences in a manually switchable omnidirectional/directional digital hearing aid. The two microphone modes were compared in a variety of everyday listening situations encountered by the participants over a four-week period, using a paper and pencil log form that was completed by the participant. Eight of the participants, selected at random, wore the device programmed with the OMNI mode in memory 1 and the DIR mode in memory 2, whereas the remaining nine participants wore the test hearing aid with DIR programmed into memory 1 and OMNI programmed into memory 2. These were referred to as "program #1" and "program #2" to the participants. They were told that these programs processed sound differently, similar to the two programs in their own hearing aids. However, they were not given any details regarding the type of signal processing provided by either program.

Participation in the study involved two "pre-trial" periods of two weeks and one week, respectively, followed by a four-week trial during which the study field data were obtained. Progress during the four-week trial was monitored by weekly phone calls by one of the investigators. Specifically, the participant was questioned regarding adherence to the daily schedule of completing log forms, number of daily entries, details of entries, and any unforeseen problems that may have been encountered as a result of participating in the study.

Schedule of Participation

Participation in this study took seven weeks to complete and required four clinic visits. The schedule of events for these four sessions was as follows:

Session 1. Routine tests of hearing, including pure-tone audiometry, tympanometry, acoustic reflexes, and monosyllabic word recognition in quiet were administered to determine if prospective participants met the audiometric selection criteria for inclusion in the study. Next, the BTE (behind-the-ear) version of the Canta7 (Canta770D) was temporarily fit to each ear using foam earplugs without venting, and the Hearing In Noise Test (HINT; Nilsson et al, 1994) was administered for the omnidirectional and directional modes. Participants had to obtain a directional advantage of at least 1.5 dB (95% confidence interval; Nilsson et al, 1994) to be enrolled in the study. The HINT test procedures will be discussed later in this paper. If a directional advantage ≥1.5 dB was obtained, an earmold impression was made of each ear. Finally, participants were given ten blank log forms, instructed how to fill them out, and given practice with the help of one of the investigators in filling out the form in two listening environments, a large hospital lobby and a small conference room. Participants were instructed to fill out ten of these logs during the next two weeks while wearing their own hearing aids, switching regularly between the two programs (OMNI and DIR) when new listening situations were encountered.

Session 2 (approximately two weeks following Session 1). One of the investigators reviewed the ten log forms that the participants had completed during the prior two weeks to make sure that they were filling them out correctly. The ITE test instrument was custom fit to each ear, and the participants were familiarized with the operation of these devices. Participants were given another ten blank log forms and instructed to fill them out during the next week while they were wearing the test instruments.

Session 3 (approximately one week following Session 2). Participants were asked to report on how they were doing with the test hearing aids. Log forms from the previous week were reviewed to make sure that they were completed correctly, and programming adjustments to the hearing aids were made, if needed. The electroacoustic measurements described above were obtained with each instrument to make sure that it was amplifying sound as prescribed. Speech recognition ability in noise was measured in a sound-treated test booth using the HINT in the OMNI and DIR modes, and the directional advantage was computed. Finally, the participant was given a large supply of blank log forms and instructed to fill them out over the next four weeks. Detailed instructions on how and when to fill out the forms were provided.

Session 4 (approximately four weeks following Session 3). Logs from the previous four weeks were collected and reviewed. The HINT was administered again for both the OMNI and DIR modes, and the directional advantage was determined.

Hearing Aid Use Log

The Hearing Aid Use Log (HAUL) was used to record the characteristics of every listening situation encountered during a total of seven days of the four-week trial—one for each day of the week. Because it was important that the listening situations recorded be as representative as possible of listening situations normally encountered by the participants in daily living, participants were requested to complete logs in one-third day blocks of time: mornings (rising to noon) for one week, afternoons (noon to 5:00 p.m.) a second week, and evenings (5:00 p.m. to retiring) a third week. The order in which these one-third day blocks of data were acquired were assigned by the investigators and randomized across participants over the first three weeks of the four-week trial. Given that completing logs for several hours within a day may not have been possible on some days, a fourth trial week was included so that participants could make up any (one-third) days missed during the first three weeks of the trial.

During the seven days that were surveyed by each participant, every major active listening situation that was encountered was to be described, that is, every listening situation that lasted more than a few minutes. Although performance in more brief communication encounters may be significant, it was impractical to request that participants evaluate such listening situations because of the amount of time that was required to complete each log. Only listening situations in which active listening took place were included. Generally, this meant situations in which the participant was listening to speech, or actively listening to nonspeech sounds (e.g., music, sounds of nature). Listening situations that were encountered repeatedly (e.g., watching television in the participant's living room, listening to the radio in the car) were rated separately each time the person entered into the listening situation.

Participants were instructed, upon entering each new listening environment, to switch between memories 1 and 2 until they determined if one or the other was preferable. The participants then rated their preference for these two memories (microphone modes) using a three-point scale, with the middle rating indicating no preference. The HAUL used a check-box format to characterize each listening environment in terms of location (indoors, car, outdoors), the size of the indoor space (small, average, large; compared to average living room), presence or absence of carpeting, location of the primary talker/sound source (front, side, back), distance from the primary talker/sound source (<3 ft, 4–10 ft, >11 ft), presence or absence of background noise, and location of background noise (front, side/back, all around).

Based on the HAUL responses, each listening situation encountered by each participant was categorized into one of 24 PLS. Consistent with the binary model, the categories of signal location and noise location were reduced to "front" and "other," those of signal distance to "near" (≤10 feet) and "far" (≥11 feet). The latter distinction was made based on Surr et al (2002). Because reverberation was not measured directly, high- and low-reverberation environments were identified indirectly based on other environmental characteristics. Specifically, outdoor locations and the passenger compartment of automobiles were assumed to be low-reverberation environments. Indoor locations that were equal in size or smaller than an average living room were assumed to be low-reverberation environments if they were carpeted. Otherwise, they were regarded as high-reverberation environments. Indoor spaces that were larger than an average living room were assumed to be high-reverberation environments.

Participants also indicated on the HAUL the duration (in minutes) they were communicating/listening in each situation. Finally, they rated the listening situation as either easy or difficult. The latter determination was made while wearing the hearing aids in the preferred microphone mode.

At the end of the trial period, participants were asked to estimate the overall percentage of time they used the hearing aids in each of the two memories during those periods of the trial when they were wearing the test hearing aids but were not completing HAUL assignments. Because participants completed the HAUL for a total of one week during the month-long trial, this amounted to three-quarters of the trial period.

Speech Recognition in Noise

The HINT assesses the ability to repeat sentences in the presence of background noise. It was administered for each microphone mode on three occasions (see above). The order of testing of the OMNI and DIR programs was randomized across participants. Two 10-sentence lists (a total of 20 sentences) were presented to obtain a score. Prior to each test administration, a 10-sentence practice list was administered to familiarize the participant with the test conditions. Testing was performed in a sound-treated audiometric test suite following standard calibration procedures. Test materials were presented to the participant in the sound field with the test sentences presented through a loudspeaker positioned at 0 degrees azimuth and the competing correlated noise coming from loudspeakers at 90, 180, and 270 degrees azimuth.

Commercially available compact disc recordings of the HINT, consisting of 25 10-sentence lists, were used. Test sentences were presented in speech-shaped noise. The competing noise was presented at a fixed level of 65 dBA, and the presentation level of the test sentences was adjusted adaptively in 2 dB steps until the participant could correctly repeat half of the sentences. All words of a sentence had to be repeated correctly for a sentence to be counted as correct. The level of the test sentences (in dB) that yielded correct recognition of 50% of the sentences was recorded as the Reception Threshold for Sentences (RTS in dB).

The test sentences and the competing noise were digitized, and computer-controlled adjustments of the attenuator were made in response to the tester's manual indication of correct or incorrect responses. The directional advantage was derived automatically using the following definition of the directional advantage (DA):

$$DA = RTS_{OMNI} - RTS_{DIR}$$

RESULTS

Hearing in Noise Test

The mean omnidirectional and directional RTS for the three administrations of the HINT are summarized in Figure 4. The average directional advantage for the screening, pre-trial, and post-trial administrations were 4.6, 3.9, and 3.3 dB, with standard deviations of 1.9, 1.5, and 2.8, respectively. Individual

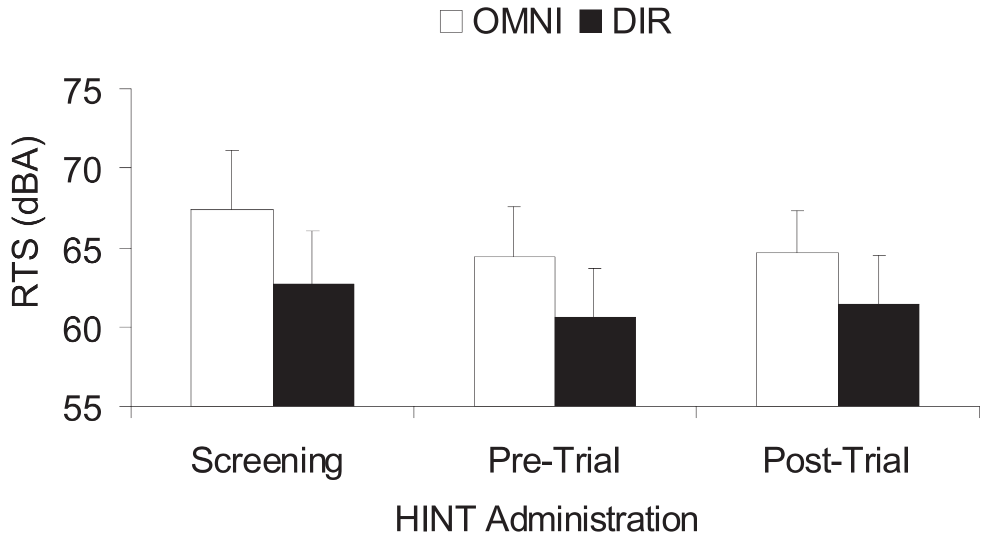


Figure 4. Mean RTS scores for the omnidirectional mode and the directional mode for administrations of the HINT. The error bars indicate one standard deviation.

scores ranged from -1.9 to 9.0 dB across the three sessions. These data are consistent with those of Ricketts (2000) for a variety of noise source locations and testing environments. A two-factor repeated measures analysis of variance (ANOVA) of the RTS data revealed significant main effects for microphone mode ($F = 38.4$; $p < .001$) and test session ($F = 6.03$; $p < .005$). Significantly lower RTS scores (better sentence recognition in noise) were observed for the directional mode, across the three administrations of the test. Further, significantly higher RTS scores were obtained for the initial screening administration of the HINT with the BTE hearing aids compared to the two administrations with the ITE instruments. The interaction between microphone mode and test session was not statistically significant. A separate ANOVA was performed on the pre-trial and post-trial HINT data with the ITE test instruments and revealed that the main effect for microphone mode was significant ($F = 24.05$; $p < .001$). However, the main effect for test session was not significant ($F = 0.58$; $p = .45$), and the interaction between microphone mode and test session was not significant. These results, therefore, indicated that mean performance with the test instrument did not differ significantly between the pre-trial and post-trial administrations of the HINT.

Description of Everyday Listening Situations

Recall that each participant was required to complete a HAUL for every active listening situation (other than brief communication encounters) that occurred during (a total of) seven days. Hence, the number of listening situations that were recorded depended on the nature and extent of each participant's daily activities. A total of 1599 listening situations was described. The mean number of logs (i.e., listening situations) completed by each of the 17 participants was 94.1 (SD: 39.1; range: 54–185). Each was categorized into one of the 24 PLS, based on the data recorded on the HAUL describing that listening environment. Three examples of specific listening situations described by the participants under 21 of the 24 PLS are provided in the Appendix. Only two examples are provided for PLS14 because only two descriptions within this PLS were obtained. No examples for PLS6 and PLS16 are given because none were encountered by the participants.

Because participants completed a new HAUL each time a different listening situation was encountered, no matter how often it was encountered in daily living, many of the listening situations recorded for a given participant are of the same listening environment. By allowing duplicate

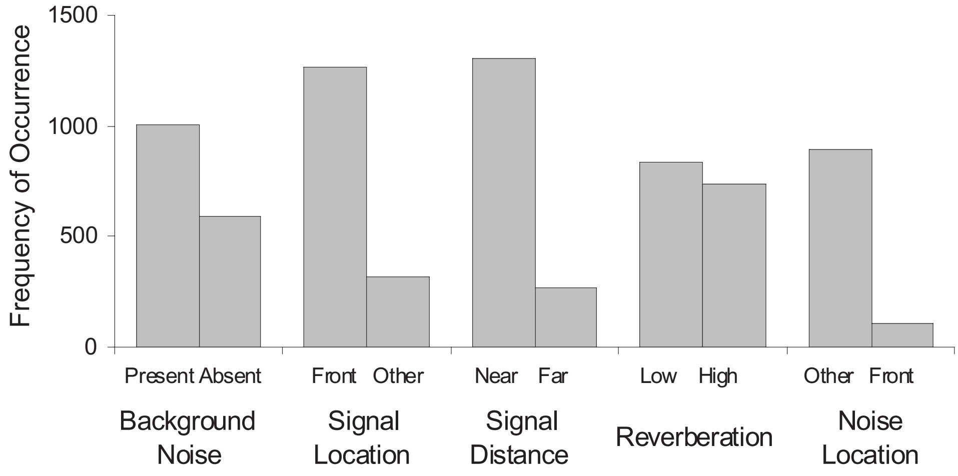


Figure 5. Distribution of the listening situations for each of the five environmental variables described by the model, pooled across the other four variables.

descriptions, the 1599 listening situations represent the range of listening situations encountered by these hearing-impaired adults weighted by the frequency with which each type of listening situation is encountered. Further, participants were required to estimate the total length of time that they were in each listening situation. These data provide additional importance weighting information regarding the listening situations, which will be described later in this section.

The frequencies of occurrence of listening situations according to the five environmental variables of interest are summarized within the parentheses in Figure 1. Each row represents the distribution of the total listening situations described by the participants according to one or more of the environmental variables. It should be noted that the row totals do not add up to 1599 in every case, as participants occasionally failed to fill in some information about listening situations on their logs. The first row (background noise) categorizes the listening situations according to whether noise was present or absent. In this case, 1006 listening situations were described in which noise was present, and 593 situations were described in which noise was absent. Rows two through five further subdivide the total listening situations according to signal location, signal distance, reverberation, and noise location. Because noise location does not apply to the 593 situations in which noise was absent, there are no data entered for these situations in the noise location row.

Although Figure 1 provides a complete accounting of frequency of occurrence of listening situations according to the model, the distribution of the listening situations according to each of the five variables independently is not easily deciphered from these data, other than for the first variable (row 1: background noise, present or absent). The frequency of occurrence of listening situations for each of the five environmental variables, pooled across the other four environmental variables, is shown in Figure 5. It is apparent that the most commonly occurring listening situations encountered by the participants involved a signal location in front of the listener and relatively near. Background noise was often present but rarely reported as located in front of the listener. Finally, environments that were categorized as low reverberation and as high reverberation were encountered with almost equal frequency.

Table 1 lists each of the 24 PLS described by the model according to frequency of occurrence, from the PLS that was encountered most frequently by the participants (PLS1) to the two PLS that were never encountered (PLS6 and PLS16). The

Table 1. The 24 Prototype Listening Situations Ranked by Frequency of Occurrence

PLS	BN	Signal Location	Signal Distance	Reverberation	BN Location	Frequency	Percentage
1	Present	Front	Near	Low	Other	301	19.1
3	Present	Front	Near	High	Other	275	17.5
18	Absent	Front	Near	High		220	14.0
17	Absent	Front	Near	Low		201	12.8
9	Present	Other	Near	Low	Other	122	7.8
20	Absent	Front	Far	High		64	4.1
2	Present	Front	Near	Low	Front	45	2.9
5	Present	Front	Far	Low	Other	44	2.8
13	Present	Other	Far	Low	Other	44	2.8
7	Present	Front	Far	High	Other	43	2.7
11	Present	Other	Near	High	Other	39	2.5
21	Absent	Other	Near	Low		39	2.5
4	Present	Front	Near	High	Front	36	2.3
15	Present	Other	Far	High	Other	20	1.3
19	Absent	Front	Far	Low		19	1.2
22	Absent	Other	Near	High		16	1.0
24	Absent	Other	Far	High		13	0.8
23	Absent	Other	Far	Low		11	0.7
8	Present	Front	Far	High	Front	10	0.6
10	Present	Other	Near	Low	Front	6	0.4
12	Present	Other	Near	High	Front	3	0.2
14	Present	Other	Far	Low	Front	2	0.1
6	Present	Front	Far	Low	Front	0	0
16	Present	Other	Far	High	Front	0	0
					Total:	**1573**	**100.0**

first data column (Frequency) gives the number of listening situations encountered by the participants for each PLS, and the second data column shows the frequency of each PLS in percent (Percentage) of the total listening situations encountered. Hence, the most frequently encountered type of listening situation involved background noise present and located other than in front of the listener, the signal located in front of the listener and relatively near, and relatively low reverberation (PLS1). Such listening situations constituted 19.1% of all listening situations encountered by the participants.

Table 2 gives the average time, in minutes, that the 17 participants reported being in each of the PLS. These data are organized similarly to the frequency of occurrence data in Table 1, with the PLS listed according to the average time that participants remained in each, from the longest (PLS24) to those that were never encountered (PLS6 and PLS16). It is notable that the average length of time that participants reported being in the PLS with the longest average duration (PLS24) was 151.3 minutes, or more than two and a half hours. The average length of time that participants reported being in the PLS with the shortest average duration (PLS12) was nearly 19 minutes. Hence, reflecting the time required to assess a listening situation and fill out the HAUL, participants generally completed logs on listening situations that lasted several minutes, and brief communication encounters were infrequently reported.

Figure 6 shows the average time (in minutes) that participants remained in listening situations, for each of the five environmental variables pooled across the other four variables. Thus, for example, the average time spent in listening situations where background noise was present was 49.7 minutes, whereas the average time that they spent in listening situations where

Table 2. The 24 Prototype Listening Situations Ranked by Average Time Spent in Them

PLS	BN	Signal Location	Signal Distance	Reverberation	BN Location	Time (minutes)
24	Absent	Other	Far	High		151.3
13	Present	Other	Far	Low	Other	123.3
5	Present	Front	Far	Low	Other	75.3
23	Absent	Other	Far	Low		66.2
20	Absent	Front	Far	High		65.1
17	Absent	Front	Near	Low		59.9
19	Absent	Front	Far	Low		54.7
11	Present	Other	Near	High	Other	49.4
4	Present	Front	Near	High	Front	49.3
8	Present	Front	Far	High	Front	49.0
2	Present	Front	Near	Low	Front	48.3
9	Present	Other	Near	Low	Other	47.9
7	Present	Front	Far	High	Other	47.1
3	Present	Front	Near	High	Other	46.8
22	Absent	Other	Near	High		45.9
21	Absent	Other	Near	Low		44.6
1	Present	Front	Near	Low	Other	42.6
15	Present	Other	Far	High	Other	39.9
18	Absent	Front	Near	High		39.2
10	Present	Other	Near	Low	Front	38.3
14	Present	Other	Far	Low	Front	20.0
12	Present	Other	Near	High	Front	18.7
6	Present	Front	Far	Low	Front	0
16	Present	Other	Far	High	Front	0
					Total:	**1222.8**

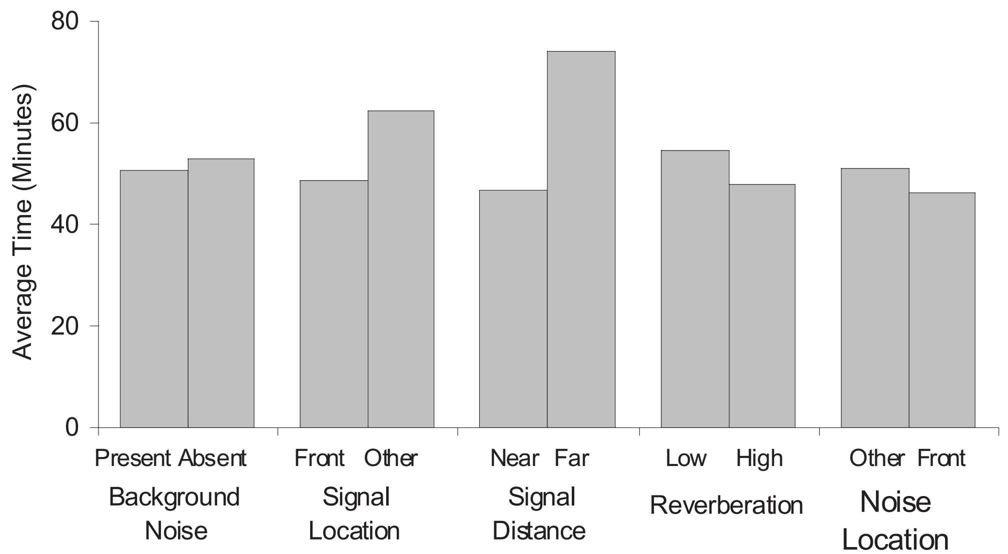


Figure 6. Average time (in minutes) spent in listening situations, for each of the five environmental variables, pooled across the other four variables.

Table 3. The 24 Prototype Listening Situations Ranked by Total Active Listening Time

PLS	BN	Signal Location	Signal Distance	Reverberation	BN Location	Time x Frequency	Percentage
3	Present	Front	Near	High	Other	12,870.0	15.9
1	Present	Front	Near	Low	Other	12,822.6	15.9
17	Absent	Front	Near	Low		12,039.9	14.9
18	Absent	Front	Near	High		8624.0	10.7
9	Present	Other	Near	Low	Other	5843.8	7.2
13	Present	Other	Far	Low	Other	5425.2	6.7
20	Absent	Front	Far	High		4166.4	5.2
5	Present	Front	Far	Low	Other	3313.2	4.1
2	Present	Front	Near	Low	Front	2173.5	2.7
7	Present	Front	Far	High	Other	2025.3	2.5
24	Absent	Other	Far	High		1967.0	2.4
11	Present	Other	Near	High	Other	1926.6	2.4
4	Present	Front	Near	High	Front	1774.8	2.2
21	Absent	Other	Near	Low		1739.4	2.2
19	Absent	Front	Far	Low		1039.3	1.3
15	Present	Other	Far	High	Other	798.0	1.0
22	Absent	Other	Near	High		734.4	0.9
23	Absent	Other	Far	Low		728.2	0.9
8	Present	Front	Far	High	Front	490.0	0.6
10	Present	Other	Near	Low	Front	229.8	0.3
12	Present	Other	Near	High	Front	56.1	0.1
14	Present	Other	Far	Low	Front	40.0	0.0
6	Present	Front	Far	Low	Front	0	0
16	Present	Other	Far	High	Front	0	0
					Total:	**80,827.5**	**100.0**

background noise was absent was 52.1 minutes. In general, the length of time that participants tended to stay in a listening situation did not vary greatly with the environmental variable. On average, participants tended to stay in active listening situations around 45–60 minutes. The most notable exception to this general trend was for the signal distance variable. The average time spent in listening situations in which the signal was relatively near (≤10 feet) was 47.0 minutes, whereas the average time spent in situations where the signal was relatively far was 74.7 minutes. There was some tendency for participants to stay longer in listening situations where the signal was located other than in front, compared to in front of the listener.

A comparison of Tables 1 and 2 suggests that the PLS that were encountered most often were not necessarily the ones in which the participant stayed the longest. That is to say, the order in which the PLS are listed in these two tables is not the same. This observation was confirmed statistically by computing a Spearman Rank Correlation between the rank scores (1–24) for the 24 PLS in Table 1 with those in Table 2. The resulting Spearman correlation coefficient was 0.36, suggesting only a modest relationship.

Table 3 combines the data presented in Tables 1 and 2. Specifically, the frequency of occurrence of the 24 PLS (from Table 1) was multiplied by the average time that participants reported being in each of these 24 types of listening situations (from Table 2). The resulting products are shown in the first data column (Time x Frequency). These products were then normalized by dividing each by the sum of all 24 products. This resulted in 24 percentages (totaling 100%) that estimate the percentage of the participants' total active listening time in each of the 24 PLS. The 24 listening situations are ordered from the one in which the

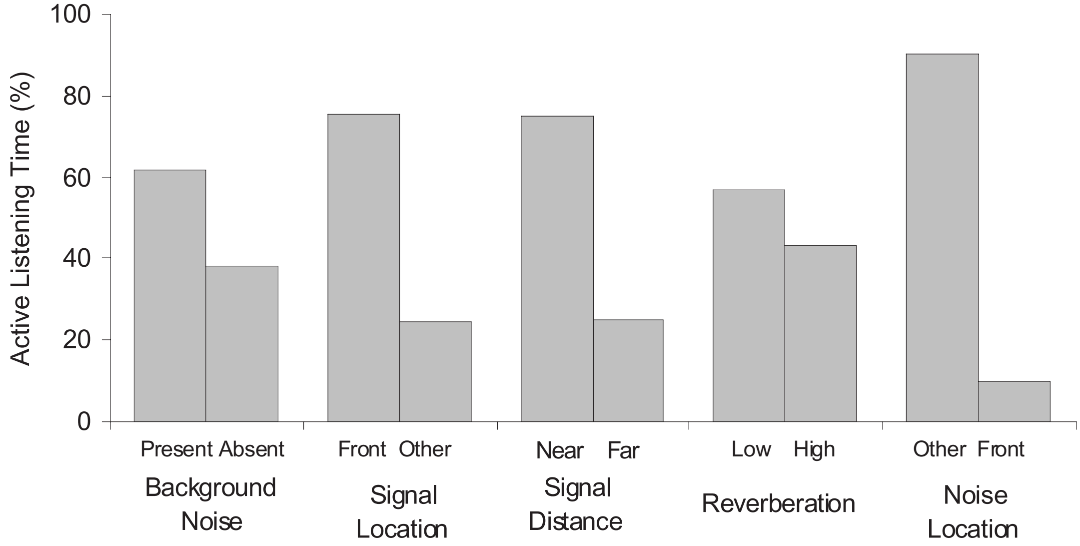


Figure 7. Active listening time (frequency of occurrence x average duration), in percent, for each of the five environmental variables described by the model, pooled across the other four variables.

participants spent the largest part of their active listening time to the situation in which they listened the least. The data in Table 3, therefore, represent an importance weighting of the 24 PLS included in the study. Presumably, the more problems that a patient reports in situations accounting for a larger portion of their active listening time, the more handicapping the hearing impairment. Similarly, the better a hearing aid is able to improve listening performance in situations accounting for a larger portion of a patient's active listening time, the greater the perceived aided benefit to that patient.

An additional observation about the data in Table 3 concerns the amount of active listening time accounted for by the HAUL. A total of 80,827.5 minutes of active listening were recorded by the participants. If this number is divided by 17 (the number of participants), and by 7 (the total number of days that each participant completed logs), the result is 679.2 minutes. This is the average number of minutes per day that were accounted for by each participant, or between 11 and 12 hours per day.[1] If it is assumed that participants were awake an average of 16 hours per day (960 minutes), the HAUL data accounted for approximately 71% of total trial time that participants were awake and might be wearing their hearing aids and engaging in active listening. The remaining time was most likely accounted for by periods during the day when they were not actively listening (e.g., reading the paper, working at the computer) and/or not wearing the hearing aids, as well as by brief periods of active listening that, as previously noted, tended not to be recorded by the participants.

Figure 7 summarizes active listening time (frequency of occurrence x average duration) according to each of the five environmental variables, pooled across the other four variables. Data for each environmental variable are presented as percentages of total active listening time. For example, participants reported being in environments in which noise was present 61.8% of the time, and in environments in which noise was absent 38.2% of the time. Based on these data, hearing-impaired persons spend relatively more active listening time in listening environments where noise is present and is located other than in front, and the signal is located in front of and relatively near to the listener. Relatively equal amounts of time are spent in listening environments with relatively low reverberation as with relatively high reverberation.

Microphone Preferences

Recall that participants were required

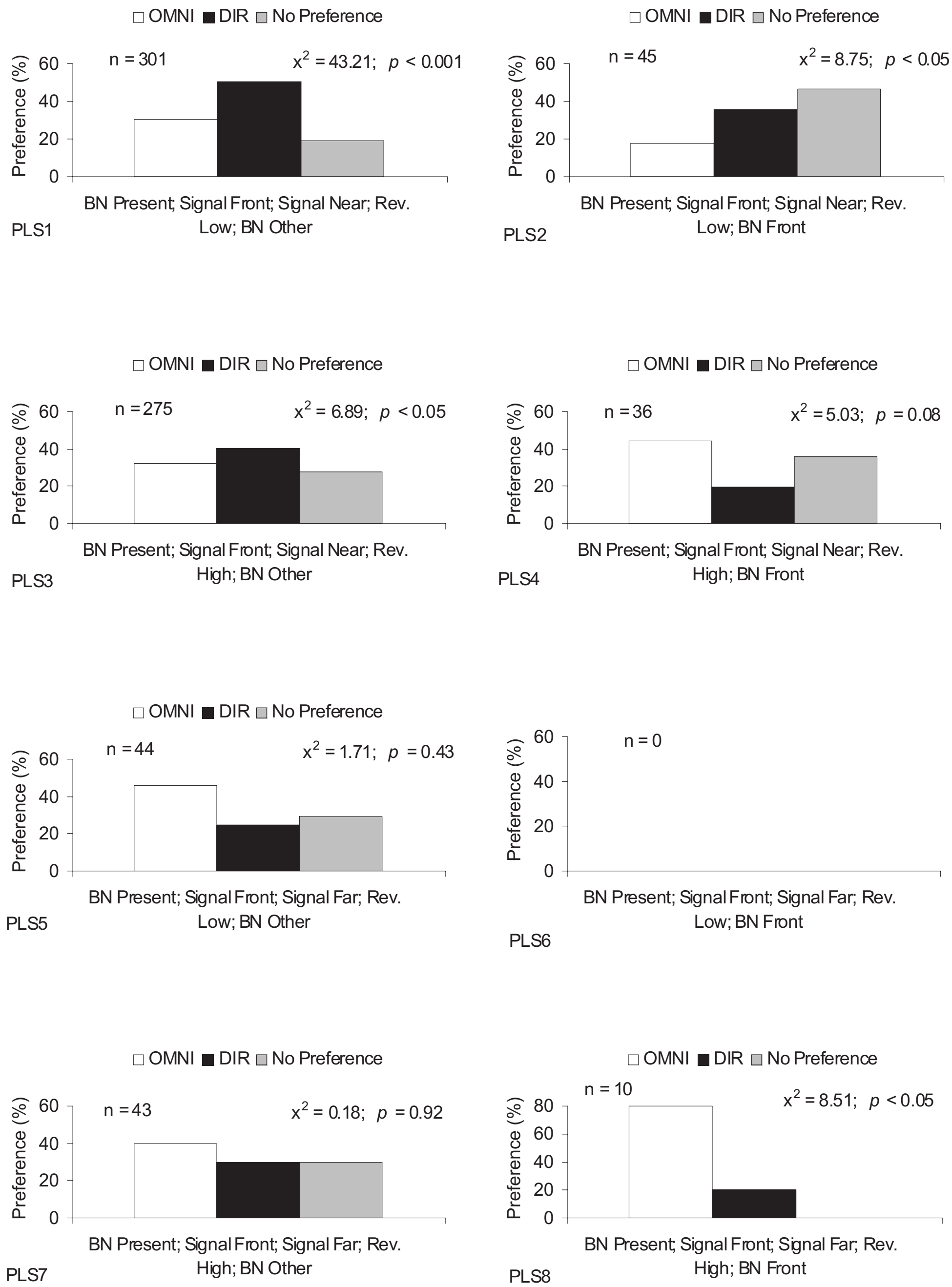


Figure 8a. Distribution of the microphone preference ratings (%) for prototype listening situations 1–8 described by the model. The chi square statistic compares the distribution of preference ratings for each PLS to the overall distribution for all 1599 listening situations.

to switch between the omnidirectional and directional modes of the test instruments in every major listening situation that was encountered (for a total of one week during a one-month period) and to determine if either microphone mode was preferred or if there was no preference. None of the three preference categories dominated participant ratings. Expressed as percentages of the 1599 listening situations, the omnidirectional mode was favored in 37.4%, the directional mode in 33.0%, and there was no preference for either microphone mode in the remaining 29.6%. Although these mean percentages suggest a relatively similar distribution of preferences for the three categories across participants,

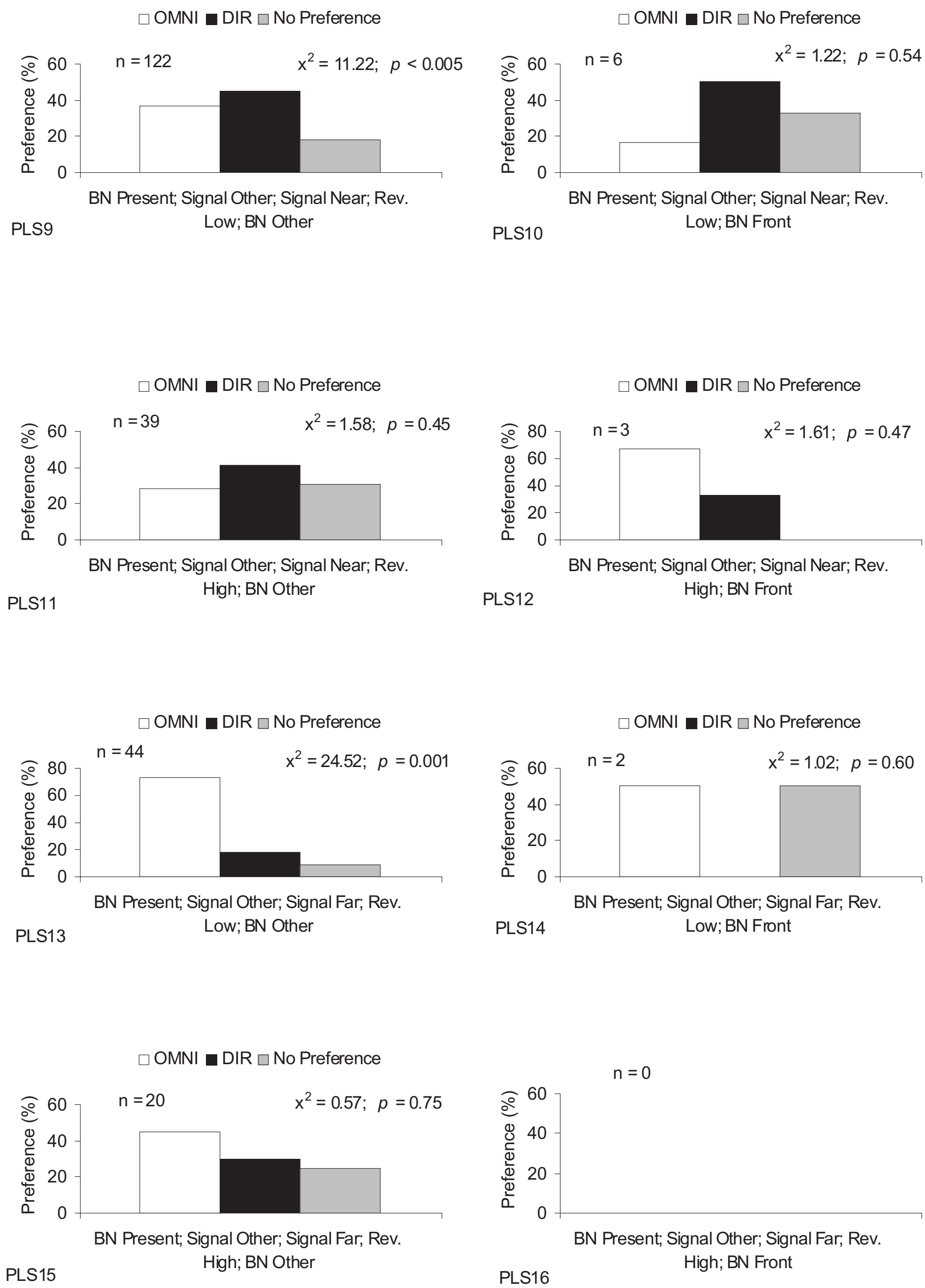


Figure 8b. Distribution of the microphone preference ratings (%) for prototype listening situations 9–16 described by the model. The chi square statistic compares the distribution of preference ratings for each PLS to the overall distribution for all 1599 listening situations.

individuals varied considerably. For example, one participant preferred the omnidirectional mode in 90% of all the listening situations encountered, while another preferred the directional mode in 73% of listening situations. The most extreme participant, in this regard, did not prefer either microphone mode in 99% of all listening situations that he encountered during the trial.

Figure 8 shows the breakdown of participant ratings for each of the 24 PLS described by the model. It is clear that the relative frequencies of the three preference ratings varied across the PLS. Hence, microphone preferences interacted with the listening environment. This observation was confirmed statistically via a chi square analysis. The chi square statistic associated

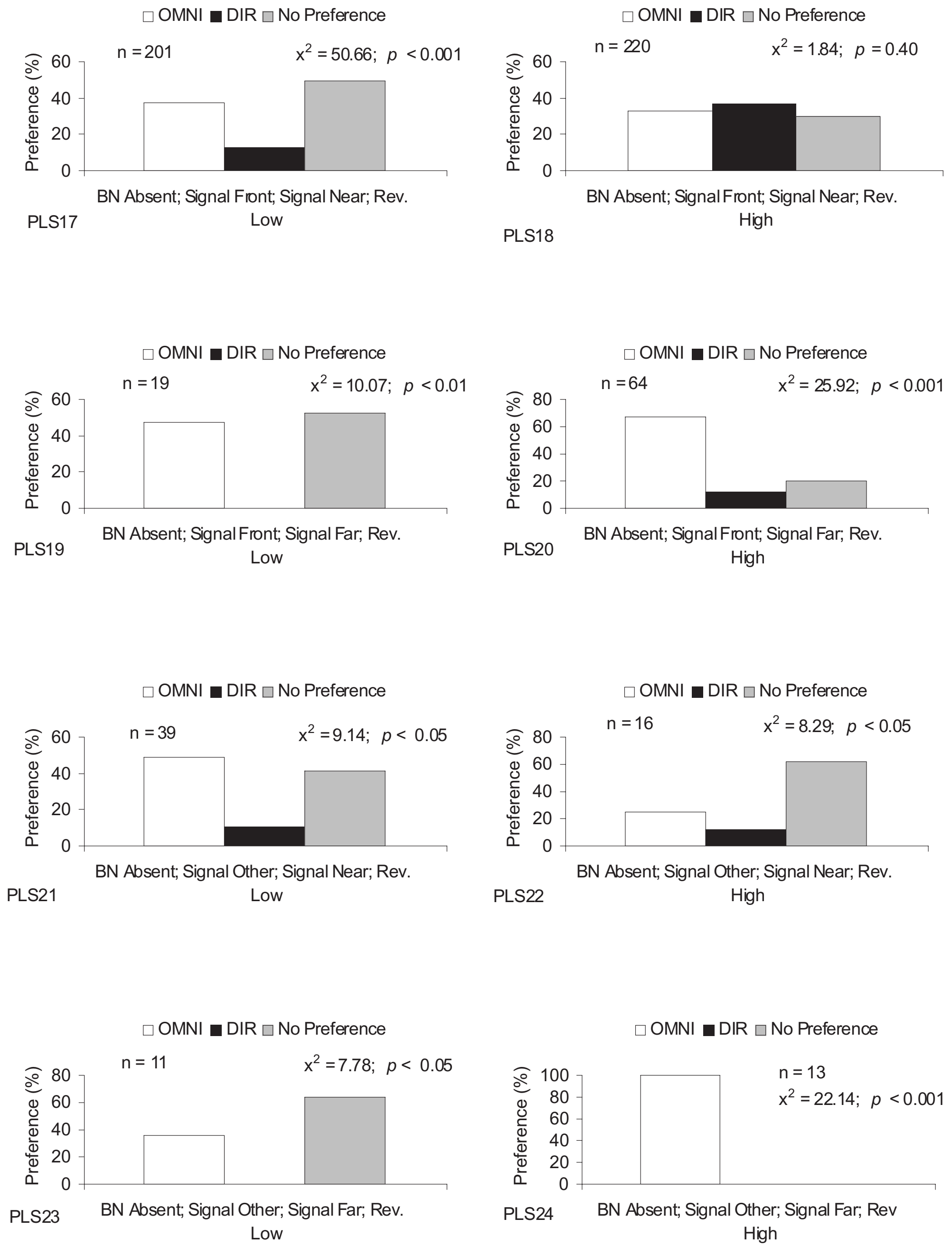


Figure 8c. Distribution of the microphone preference ratings (%) for prototype listening situations 17–24 described by the model. The chi square statistic compares the distribution of preference ratings for each PLS to the overall distribution for all 1599 listening situations.

with each panel compares the distribution of preference ratings for each listening situation to the mean distribution for all 1599 listening situations given above. Statistical significance $(p < .10)^2$ was achieved in 14 of the 19 PLS for which at least ten descriptions were obtained. These data, therefore, suggest that the characteristics of the listening environment significantly influenced microphone preference in the majority of listening situations encountered.

Predicting Microphone Preferences

This section describes the extent to which microphone preference can be predicted from the characteristics of everyday listening

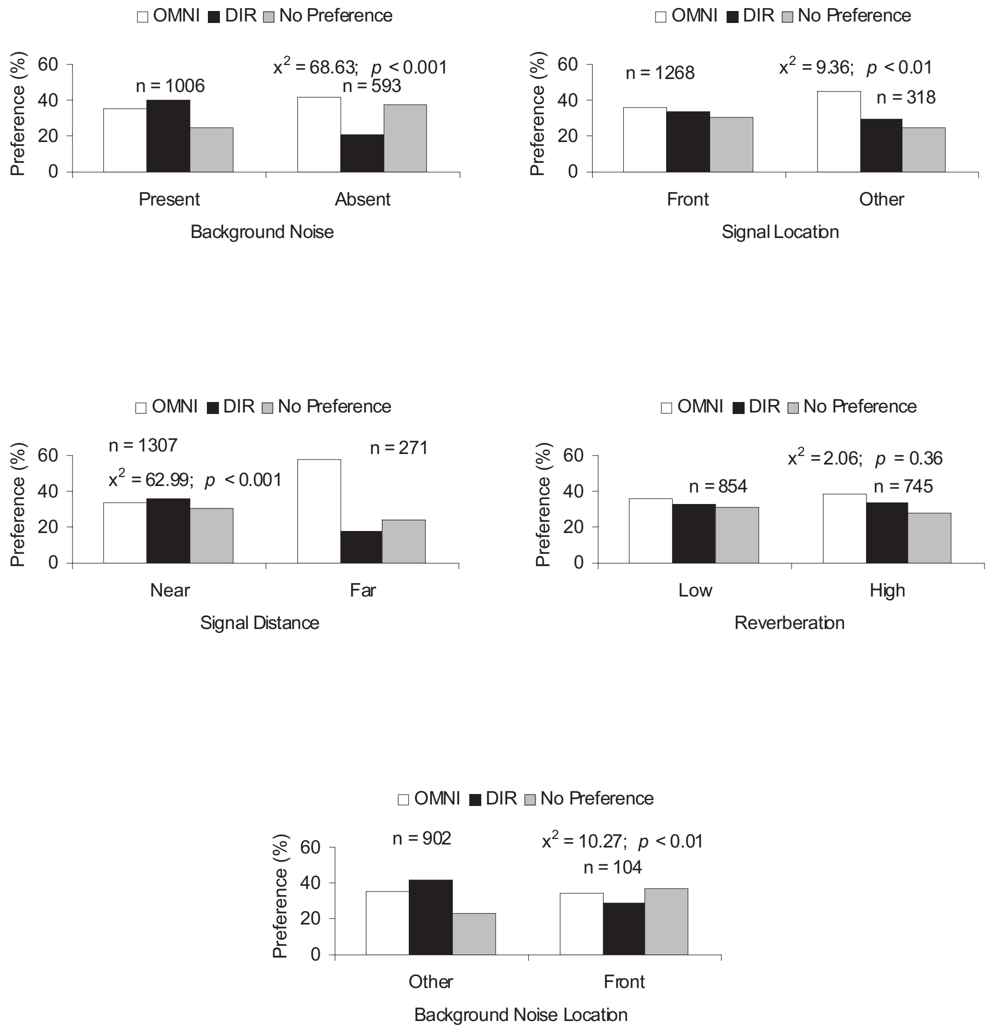


Figure 9. Distribution of microphone preferences (%) for each of the environmental variables included in the model. The chi square compares the two distributions in each panel.

situations. This will be explored within the framework of the model in Figure 1. Figure 9 reports the distribution of microphone preferences for each environmental variable included in the model. The data in each panel provide the distribution for each binary condition of that variable, pooled across the other four variables. The chi square statistic for each panel compares the two distributions within that panel; that is, the distribution of microphone preferences for each binary condition of that environmental variable. The chi square statistic was significant for four of the five environmental variables. The distribution of microphone preferences did not differ significantly for listening situations with relatively low reverberation compared to those with relatively high reverberation. For the background noise variable, there was a slight preference for the directional mode when noise was present and a rather distinct preference for the omnidirectional mode when noise was absent or no preference was expressed. There was no significant preference for either microphone mode when the signal was located in front of the listener. However, there was a distinct preference for the omnidirectional mode when the signal was located other than in front. Similarly, there was no distinct preference for either microphone mode when the signal source was near, but a very distinct preference for the omnidirectional mode when the signal was located relatively far away. Finally, for the background noise location variable, there was a slight preference for the directional mode

Table 4. Prototype Listening Situations Grouped by Microphone Preference

PLS	BN	Signal Location	Signal Distance	Reverberation	BN Location
Omnidirectional					
4	Present	Front	Near	High	Front
5	Present	Front	Far	Low	Other
8	Present	Front	Far	High	Front
13	Present	Other	Far	Low	Other
17	Absent	Front	Near	Low	
19	Absent	Front	Far	Low	
20	Absent	Front	Far	High	
21	Absent	Other	Near	Low	
24	Absent	Other	Far	High	
Directional					
1	Present	Front	Near	Low	Other
2	Present	Front	Near	Low	Front
3	Present	Front	Near	High	Other
No Preference					
7	Present	Front	Far	High	Other
9	Present	Other	Near	Low	Other
11	Present	Other	Near	High	Other
15	Present	Other	Far	High	Other
18	Absent	Front	Near	High	
22	Absent	Other	Near	High	

when the background noise was located other than in front of the listener, and a slight preference for the omnidirectional mode when the noise source was located primarily in front or no preference was expressed. Overall, the data depicted in Figure 9 suggest that the influence of the presence or absence of background noise, signal location, and signal distance are greater than those of reverberation and background noise location. Notably, preferences for the omnidirectional mode largely appear to account for the significant differences observed.

A primary purpose of this study was to provide guidance to hearing-impaired patients fit with switchable omnidirectional/directional hearing aids regarding the microphone mode (OMNI or DIR) most likely to be preferred in various types of everyday listening situations. To address this issue, the no preference ratings were deleted from the analysis. The rationale here was that the hearing aid must be set in one microphone mode or the other in every listening situation encountered. Hence, even if there were a substantial number of no preference ratings for a particular PLS, if one of the two microphone modes was significantly preferred to the other, it was regarded as the preferred mode for that PLS. A chi square statistic was computed for each PLS comparing the observed distribution of OMNI and DIR microphone preferences to a 50/50 chance preference. Prototype listening situations for which fewer than five descriptions were provided by the participants (PLS6, PLS10, PLS12, PLS14, PLS16, PLS23) were not included in this analysis. Five of these six PLS involve background noise located in front of the listener, which appears to occur relatively infrequently in daily listening (see Figure 1).

Table 4 categorizes the 18 PLS for which at least five descriptions were obtained according to the microphone preference category. The omnidirectional mode was significantly preferred ($p < .10$) in nine PLS; the directional mode was significantly preferred in three PLS; and no significant preference for either mode was expressed in the remaining six PLS. Inspection of the environmental characteristics of the PLS with each of these three groups reveals some consistent trends. First, five of the nine PLS where the omnidirectional mode was preferred involved the absence of background noise. Further, in three of the four PLS where background noise was present and the omnidirectional mode was significantly preferred, the signal source was located relatively far from the listener. In contrast,

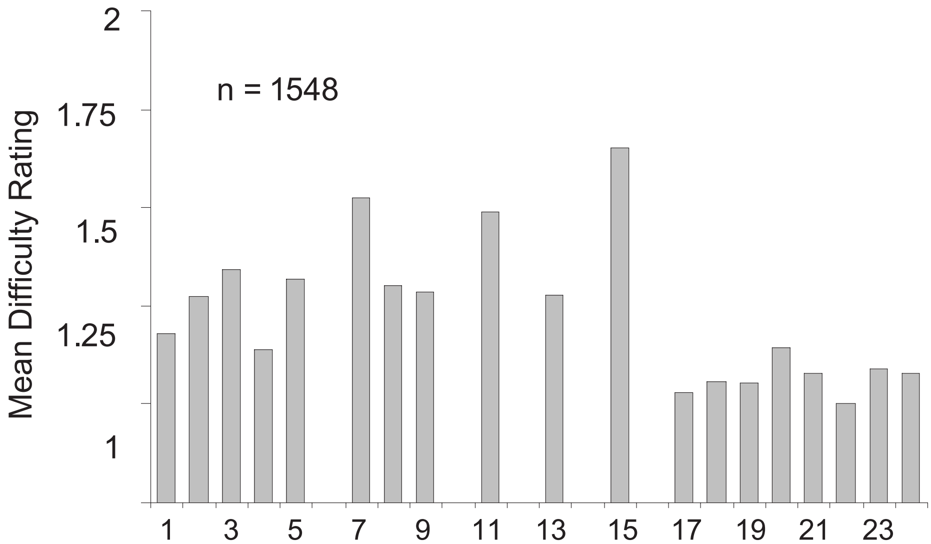


Figure 10. Mean difficulty ratings for each of the 19 prototype listening situations that were encountered at least ten times by the participants.

noise was present in each of the three PLS where the directional mode was preferred, as well as the signal being in front of and near to the listener.

Table 4, like Figure 9, suggests that the presence/absence of background noise, signal location, and signal distance may have a greater influence on microphone preferences than reverberation and noise location. Assuming that it does not make any difference which of the two microphone modes are activated for the six PLS within the "no preference" category in Table 4, we may ask: Can only these three environmental variables accurately predict the preferred microphone mode for the remaining 12 PLS where a significant preference was expressed for one microphone mode or the other? If the directional mode were activated only when background noise is present and the signal is in front of and relatively close to the listener (otherwise the hearing aid would remain in the omnidirectional mode), the device would be set in the less preferred microphone mode only in PLS4 listening situations (BN [background noise] present, signal front, signal near, reverberation high, BN location front). In this case, a preference for the directional

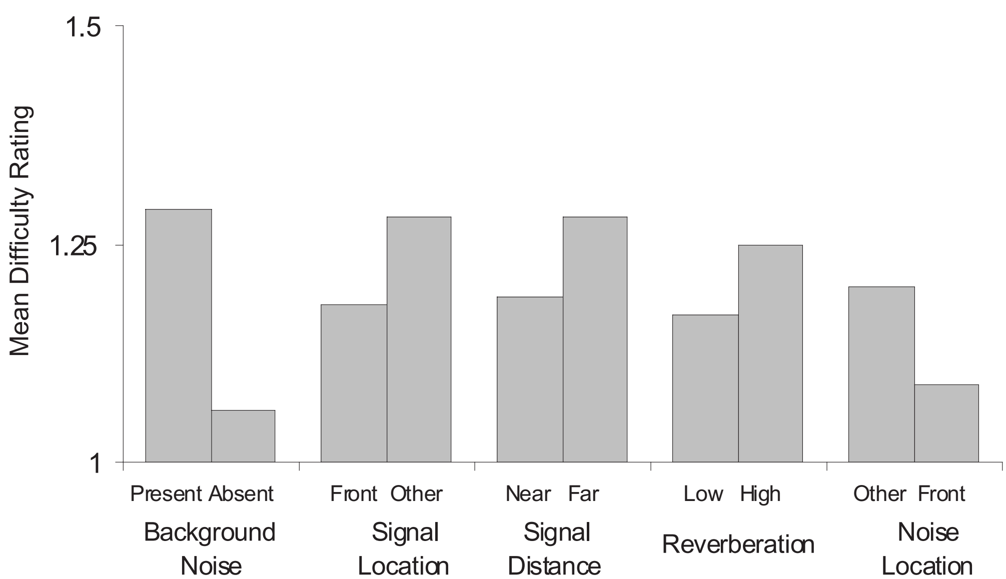


Figure 11. Mean difficulty ratings of listening situations grouped according to the five environmental variables.

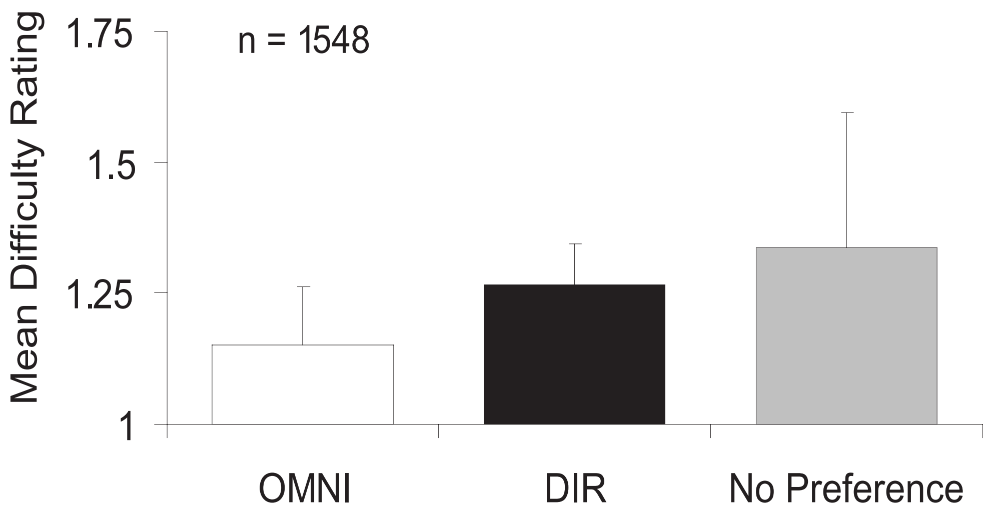


Figure 12. Mean difficulty ratings of the listening situations grouped according to microphone preference category. The error bars indicate one standard deviation.

mode would be predicted, whereas the omnidirectional mode is actually significantly preferred. However, referring to Table 3, such listening situations constituted an average of only 2.2% of the participants' active listening time.

Overall, these data suggest that the omnidirectional mode will be preferred in most listening situations, or neither microphone mode will be preferred. Only in rather specific listening environments—generally those where background noise is present and the signal is located in front of and relatively close to the listener—will the directional mode be preferred. However, again referring to Table 3, such listening situations (PLS1, PLS2, PLS3) constituted more than one-third of the total active listening time of the study participants.

Difficulty of Prototype Listening Situations

Participants were required to rate each listening situation encountered as either easy or difficult. This rating was assigned based on aided performance in the preferred microphone mode. Of the 1585 listening situations that received a difficulty rating from the participants, 1261 (79.6%) were regarded as relatively easy and 324 (20.4%) as relatively difficult. For purposes of analysis, listening situations labeled as "easy" and as "difficult" were assigned numerical values of 1 and 2, respectively. The mean difficulty rating for each of the 19 PLS that were encountered at least ten times by the participants is shown in Figure 10. As expected, a rather clear distinction existed between the PLS involving background noise (PLS1-16) and those where background noise was absent (PLS17–24). This is seen more clearly in Figure 11, which depicts mean difficulty ratings according to each environmental variable.

Figure 12 shows the mean difficulty rating of these 1548 listening situations grouped according to microphone preference category. Overall, listening situations in which the omnidirectional mode was preferred were rated as easier than listening situations in which the directional mode was preferred. Notably, listening situations in which neither microphone mode was preferred were regarded as most difficult. A chi square analysis comparing the number of easy and difficult ratings assigned to each of the three microphone preference categories revealed a significant difference ($\chi^2 = 34.89$; $p < .001$) among the difficulty ratings of the listening situations depending on the preferred microphone mode.

Microphone Mode Use Pattern

Recall that participants were engaged in filling out the HAUL a total of seven days during the four-week trial period. During the first three weeks, participants filled out logs during morning, afternoon, or evening blocks of time. The final week was devoted to completing any HAUL assignments that were missed during the first three weeks of the trial. However, participants typically completed their assignments during the first three weeks. Consequently, during two-thirds of the first three weeks of the trial, and during the fourth week, participants simply wore the test hearing aids as they would ordinarily use their own hearing aids. During the final session, following the four-week trial, the participants were asked to estimate the percentage of time that they wore the instruments set in program #1 and in program #2 during those times when HAUL assignments were not being completed. The mean estimated use pattern for the test hearing aids was 61.8% for the omnidirectional mode and 38.2% for the directional mode. This pattern reflected somewhat less use of the omnidirectional mode (and greater use of the directional mode) than for the participants' own hearing aids (73.2% and 26.8%, respectively). Inspection of the data for individual participants revealed a diverse pattern of usage, ranging from one participant who reported using the omnidirectional mode 95% of the time to two others who reported using the directional mode 90% of the time. Further, it did not appear that the default mode had a significant influence on the use pattern. Average use of the omnidirectional mode was 65.0% for the eight participants for which the default setting was the omnidirectional mode, compared to 58.9% for the nine participants for which the default setting was the directional mode.

DISCUSSION

Descriptions of Everyday Listening Situations

To the extent that the 17 participants of this study are representative of the broader population of hearing-impaired adults, the 1599 listening situations encountered and described by the participants of this study during the field trial provide a representation of the everyday listening environments of these patients. Because the primary purpose of this study was to determine the extent to which microphone mode preferences in everyday living could be predicted from the characteristics of the listening environment, descriptions of the listening environments were in terms of variables thought to influence preferences for omnidirectional and directional microphones. However, these five variables (presence/absence of background noise, signal location, signal distance, reverberation, location of noise) are known to influence hearing aid performance and benefit in general (see, for example, Nabelek and Mason, 1981).

Perhaps the first observation that may be made about the everyday listening environment of hearing-impaired adults is that it is perceived to be noisy. Background noise was reported to be present in the majority of the 1599 listening situations encountered by the participants (see Figure 5). Further, of the total active listening time documented by the participants, 61.8% was characterized as noisy and only 38.2% as relatively quiet (see Figure 7). It is well documented that hearing aids generally provide greater benefit under relatively quiet listening conditions, compared to less favorable signal-to-noise ratios (SNR; see, for example, Walden et al, 2000). This is especially true for the relatively high input levels that often characterize noisy listening situations where audibility contributes little to the reduction in speech understanding. In such listening environments, performance with hearing aids (at least those with only an omnidirectional microphone) may be no better than unaided performance for many patients. Given the limited ability of omnidirectional microphone hearing aids to improve speech understanding in background noise, there is little wonder that difficulty communicating in noisy listening situations is a common complaint of hearing aid wearers, and an important reason for the less than optimal acceptance and use of hearing instruments among the hearing-impaired population (Kochkin, 2002).

Clearly, in most listening situations encountered in daily living, the signal source is located in front of the listener. In all probability, this simply reflects the tendency for listeners to position themselves in front of a signal source whenever possible. We tend to face a talker when in conversation with another person, sit in front of the television, face the loudspeakers when listening to music, and so forth. Yet, in 20% of listening situations, and for a quarter of all active listening time, the listener does not (or cannot) face the signal source, for example, when riding in an automobile or sitting at a conference table. Obviously, such listening situations present a particular challenge to hearing aid performance, especially for devices equipped with directional microphones. For the vast majority (approximately 83%) of listening situations encountered in daily life, the signal source is relatively close to the listener, that is, within ten feet. It should be noted that the distinction between "near" and "far" (≤10 feet, ≥11 feet, respectively) was based on the findings of Surr et al (2002). It is unlikely that this distinction corresponds to the critical distance (the distance for which direct and reflected sound pressures are equal and, therefore, directional microphones may be minimally effective; Ricketts and Mueller, 1999) in most everyday listening environments. Regardless, in those noisy listening situations where the signal source is relatively far away, aided performance is likely to suffer. Obviously, the efficiency of directional microphones will diminish in reverberant environments as the distance from the signal source is increased. However, it is likely that aided performance with standard omnidirectional microphones will suffer as well. Although talkers will often raise their voices in background noise when the listener is at a distance, it is still likely that the SNR at the listener's ear will get progressively poorer as the distance between talker and listener increases, assuming that the source of the background noise is spatially separated from the signal source. Hence, it is reasonable to expect that the perceived benefit of hearing aids in background noise will be limited when the signal is located at a distance, whether or not the instruments are equipped with directional microphones.

Slightly more listening situations encountered by the participants in daily living were categorized as low reverberant than as high reverberant. Similarly, participants reported the average length of time spent in low-reverberant environments to be slightly longer than for high-reverberant environments (see Figure 6). Recall that the distinction between low and high reverberation was made indirectly, based on the characteristics of the listening environment, primarily the size of the room and/or whether or not it was carpeted. Hence, some measurement error in this variable is inevitable. Still, it does not appear that one or the other category of listening environments is encountered predominantly in everyday listening. It is well known that high levels of reverberation have a deleterious effect on speech understanding and may limit benefit from amplification (see, for example, Walden et al, 1998, 1999). Further, reverberation may limit the efficiency of directional microphones because of reflected sound energy. To the extent that relatively high reverberation may limit hearing aid performance, the data of this study suggest that it is a commonly occurring condition in everyday listening, both in terms of the frequency with which such listening situations are encountered and the amount of time spent in these listening situations.

Results for the fifth environmental variable explored in this study—location of the background noise—suggest that the noise source is rarely located directly in front of the listener. Rather, in most noisy listening situations, the source of the noise comes primarily from the sides or back or, most commonly, is all around in the environment (see below). The primary determinant in the listener's ability to understand speech is the SNR delivered to the ear. In hearing aids with directional microphones, some spatial separation of the signal and noise sources in the listening environment is necessary for an improved SNR in the directional mode. From the perspective of this environmental variable, the most problematic listening situations are those where the signal and noise come from the same location. Fortunately, it appears that this condition occurs relatively infrequently in everyday listening. However, it is also probably the case that the noise is all around in most noisy listening situations, rather than localized to one specific location to the sides or behind the listener. The participants of this study perceived the noise to be "all around" in 762 (75.7%) of the 1006 listening situations in which noise was present, rather than in front of, to the side of, or behind them. Given that the Canta750D defaults to a hypercardioid polar response when the adaptive algorithm cannot detect a noise peak to the sides or behind the listener, this polar response may have been activated in the majority of noisy listening environments encountered by the participants in daily living.

Table 3, which combines the frequency of occurrence data of Table 1 with the length of time data of Table 2, provides some of the potentially most useful data from this study. Four of the 24 PLS (PLS3, PLS1, PLS17, PLS18) accounted for 57.4% of the participants' active listening time. Each of these PLS involves the signal in front of and relatively near to the listener. The first two alone (PLS3, PLS1) accounted for nearly one-third of all active listening time. Background noise was present in both cases. In the other two frequently occurring PLS (PLS17, PLS18), accounting for approximately 25% of all active listening time, background noise was absent. Given that the latter two types of listening situations are relatively easy for hearing aid wearers (see Figure 10), it appears that considerable benefit to the patient can be achieved by improving speech understanding when the talker is located in front of and relatively near to the listener and background noise is present and spatially separated from the talker. Fortunately, these are the environmental conditions in which directional microphones should be especially effective.

Microphone Preferences

Traditional wisdom holds that the default setting for hearing aids equipped with switchable omnidirectional/directional microphones should be the omnidirectional mode, and the hearing aid should be switched into the directional mode only occasionally when environmental circumstances warrant. The implication is that the device will be in the omnidirectional mode most of the time. Cord et al (2002), in fact, found that patients fit with switchable omnidirectional/directional hearing aids reported, on average, that they used their hearing aids set in the directional mode only 22.3% of the time. The results of the current study suggest that, on average, the directional mode will be preferred in one-third of all listening situations encountered, and the omnidirectional mode will be preferred in approximately 37% of everyday listening situations. In approximately 30% of everyday listening situations, neither microphone mode will be preferred. Given that the omnidirectional and directional modes were preferred in relatively similar percentages of everyday listening situations, based on these data alone, it might be argued that either microphone mode could serve as the default setting. Later in this discussion, however, it will be argued that the omnidirectional mode is probably the more suitable default setting.

Clearly, microphone mode preferences depended on the acoustic characteristics of the listening environment (see Figure 8). That is to say, the overall distribution of microphone mode preferences across all 1599 listening situations was not maintained for each of the 24 PLS. Rather, the preferred microphone mode varied systematically with the characteristics of the listening environment. This finding is a prerequisite for developing effective strategies for setting the hearing aid in the optimal microphone mode based on an analysis of the listening environment.

Model Predictions

The primary purpose of this study was to determine the extent to which the microphone mode (omnidirectional vs. directional) generally preferred by hearing-impaired patients in a given listening situation is predictable from the characteristics of that environment. As has been previously noted, the everyday listening situations encountered by hearing-impaired persons are virtually infinitely variable. In order to bring some structure to the task, five binary environmental variables, which were assumed to influence microphone performance, were used to create 24 PLS. These are assumed to represent, at least to a first approximation, the range of everyday listening situations encountered in daily living.

When the influence of the five variables is considered separately (see Figure 9), it is apparent that the effect of each binary condition (noise present vs. absent, signal front vs. other, etc.) is not symmetrical. That is to say, the histograms for the omnidirectional and directional modes between the binary conditions of a given variable are not reciprocals of each other. Thus, for example, although there is a distinct general preference for the omnidirectional mode when background noise is absent, preference for the directional mode when background noise is present is less distinct. Similarly, there is a distinct general preference for the omnidirectional mode when the signal is located other than in front, but no preference for the directional mode when the signal is in front. A similar pattern is observed for signal distance, where the omnidirectional mode is clearly preferred when the signal is relatively far from the listener, but only a slight general preference of the directional mode when the signal is relatively near. Perhaps the one exception to this trend is for the background noise location variable. Here, there is a small preference for the omnidirectional mode (compared to the directional mode) when the noise is located in front of the listener, and a slightly greater preference for the directional mode when the noise is located other than in front.

The overall impression created by the microphone preference data for the five environmental variables considered separately is that preference for the omnidirectional mode may be more easily predicted from a single characteristic of the environment than preference for the directional mode. It is only when several environmental conditions exist simultaneously that a strong directional preference will exist. Consequently, the Figure 9 data suggest that it may be more important for the hearing aid to be set in the omnidirectional mode in listening situations that generally favor an omnidirectional microphone than for it to be set in the directional mode when one or two environmental conditions generally favor directional microphones. From this perspective, a conservative switching strategy of "when in doubt, stay in omnidirectional" would appear appropriate. This finding, in combination with the frequency with which no microphone preference is expressed in daily listening situations, suggests that the omnidirectional mode is the appropriate default setting, and the device should switch to the directional mode only when the characteristics of the listening environment warrant it.

The microphone preference data for each of the 24 PLS (see Figure 8 and Table 4) generally support these conclusions. Only three PLS were identified in which there was a significant preference for the directional mode, whereas nine PLS significantly favor the omnidirectional mode. However, as has been previously noted, the three PLS favoring the directional mode (PLS1, PLS2, PLS3) accounted for more than one-third of the active listening time of the participants in this study (see Table 3). Therefore, although the omnidirectional mode again appears to be the appropriate default setting for most patients, it is critically important that the device switch to the directional mode when environmental conditions favor it.

Of the five environmental variables examined in this study, three appear most useful in determining when the device should switch to the directional mode: presence/absence of background noise, signal location, and signal distance. Knowledge of only these three environmental variables provides a guide for wearers of switchable omnidirectional/directional hearing aids. Specifically, the results of this study suggest that the device should be switched to the directional mode when background noise is present, the signal source is located in front of the listener, and the signal source is relatively nearby, roughly ten feet or less. Following this simple strategy, the hearing aid will be set in the less preferred microphone mode only in one type of listening situation (PLS4)—when background noise is present, the signal source is in front and near, and reverberation is high and the background noise is located in front of the listener. However, because the participants spent only about 2% of their active listening time in such listening situations, which were rated easiest of all the PLS involving background noise (see Figure 10), the overall impact of this error would seem to be minimal for most patients.

The significant influence of signal distance on microphone preferences deserves additional comment. Discussions in the literature of the effects of signal distance on directional microphone performance generally focus on reverberation and the critical distance from the signal source in a particular listening environment where the direct and reflected sound pressures are equal (see, for example, Ricketts and Henry, 2002). As the distance between the signal source and the listener increases, the intensity of the reflected energy arriving at the hearing aid in relation to the direct energy increases. At the critical distance, direct and reflected energy are equal. Directional hearing aid technology depends on, among other things, a greater proportion of direct energy than reflected energy arriving at the front microphone. Directional microphones may be expected to provide benefit generally in near-field listening environments. Recall that the "critical distance" observed by Surr et al (2002) in our earlier field study of directional benefit was approximately 10–11 feet. Directional microphones generally appeared to provide significant benefit within this distance, but less so for greater distances. Although the critical distance is dependent on the size of the room, as well as the amount of reverberation present, it is likely that critical distance in most listening environments encountered by hearing-impaired persons is somewhat less than ten feet. It appears possible, therefore, that the influence of signal distance on microphone preferences observed in this study might involve more than simply the influence of reverberation. In addition to changes in the ratio of direct to reflected sound energy, there are other acoustic effects of increasing the distance of the listener from the signal source. The most obvious is decreased intensity due to the inverse square law. Also, as has already been suggested, it is likely that the SNR in a noisy listening environment is generally poorer as the distance between the signal source and listener increases because the listener will typically be closer to the source(s) of the background noise, except in those relatively rare listening environments where the signal and noise sources are coming from the same location.

Although full compensation of the normal 6 dB/octave roll-off in frequency response imposed by directional microphones was used in this study, participants frequently observed that overall output seemed lower when the device was in the directional mode. Although full compensation in the directional mode equates the frequency responses of the two microphone modes for signals presented from the front (see Figure 3), it does not equate for the effects of the nulls in the polar response created by the directional processing. Hence, overall output in the directional mode may often be lower than in the omnidirectional mode, and overall audibility could be affected. This may explain why there was a rather distinct preference for the omnidirectional mode when the signal source was far from the listener but a somewhat less distinct preference for the directional mode when the signal source was relatively near.

Difficulty of Listening Situations

The difficulty rating data provide a generally encouraging representation of the performance of the switchable omnidirectional/directional hearing aids like the one used in this study. Participants rated nearly 80% of the listening situations that they encountered as relatively easy while wearing the device in the preferred mode, including many listening situations where background noise was present. Yet, as expected, noisy listening situations remained more difficult on average than quiet environments. Generally, the mean difficulty ratings according to the five environmental variables (see Figure 11) were as expected; that is, background noise absent was easier than background noise present; signal sources located in front of the listener were easier than those located other than in front; signals located relatively near to the listener were easier than those located farther away; and low-reverberation environments were easier than high-reverberation environments. The mean difficulty ratings for listening situations grouped according to background noise location were, perhaps, less intuitive. On average, listening situations where the noise source was located in front of the listener (and, therefore, most often coming from the same location as the signal source) were rated as easier than situations where the noise source was located other than in front. Given that directional microphones generally cannot improve the SNR (compared to the omnidirectional mode) when the noise source is located in front, one might have expected such situations to be more difficult than those in which there was spatial separation of the signal and noise sources. Although an explanation for this finding is not apparent in the data, it may be that the SNR at the listener's ear is generally more favorable when the signal and noise sources are both at the same location in the listening environment. If, for example, a talker is speaking very near a loud noise source, she or he is likely to speak louder to be heard, thereby improving the SNR at the listener's ear. In contrast, when the noise source is spatially separated from the talker (and, therefore, closer to the listener), the talker may be less likely to raise his/her voice as much to be heard over the noise. Although directional microphones may improve the SNR slightly under such circumstances, the average improvement may be less than that resulting from the increased vocal effort that occurs when the talker is closer to the noise source.

Notwithstanding this interpretation, the difficulty data clearly suggest that the directional microphones made certain listening situations easier for the participants. The mean difficulty rating for listening situations where there was a significant preference for the directional mode revealed less difficulty than for listening situations where there was no preference for either microphone mode (see Figure 12). Inspection of the PLS where neither microphone mode provided superior performance (see Table 4) reveals that background noise was present in four of these six cases (PLS_7, PLS_9, PLS_{11}, PLS_{15}). Of these, PLS_7, PLS_{11}, and PLS_{15} tended to be the most difficult listening situations for the participants (see Figure 10). Two of these involve the signal source being located relatively far from the listener, and all three involve relatively high reverberation. To improve aided performance in background noise, therefore, it appears that the related issues of signal distance and reverberation must be addressed. Fortunately, however, such listening situations appear to constitute a rather small percentage of the active listening time of hearing-impaired patients (see Table 3). In this regard, the "good news" from the difficulty rating data is that the two PLS (PLS3, PLS1) that account for the greatest percentage of active listening time (31.8%) were rated among the easiest, on average, of the PLS involving background noise. Further, these most frequently encountered listening situations were rated as not much more difficult, on average, than those PLS where background noise was absent. It appears clear, therefore, that the directional mode can provide significant benefit in precisely those listening situations where it is most important to do so.

Microphone Mode Use Pattern

Although participants were required to switch between the omnidirectional and the directional modes in every listening situation encountered during those periods of the trial when HAUL assignments were being completed, during approximately three-quarters of the month-long trial they were free to use the devices as they wished. On average, participants reported using the hearing aids set in the omnidirectional mode the majority of the time (61.8%). This finding is generally consistent with an earlier study (Cord et al, 2002), which found that patient's fit with switchable omnidirectional/directional hearing aids reported using the omnidirectional mode approximately 78% of the time. Obviously, somewhat greater use of the directional mode was observed in the current study (38.2%) than was observed in Cord et al (22.3%), which involved patients fit with devices from a variety of manufacturers, as long as 24 months preceding their participation in the study. It is notable that the average time that patients used the test hearing aids in the directional mode during the time when they were not completing HAUL assignments (38.2%) was roughly similar to the combined active listening time for the three PLS for which there was a significant preference for the directional mode (34.5%). In this regard, it must be recalled that the participants did not explicitly know the nature of the signal processing provided by programs #1 and #2. The similarity of these numbers suggests that, with experience, patients are able to determine when directional microphones will be of benefit and appropriately set their hearing aids in that mode, consistent with the findings of Cord et al.

Although the average microphone mode use data lend themselves to the interpretations above, perhaps the most striking characteristic of these data is the variability across participants. When not completing HAUL assignments, some participants used the omnidirectional mode almost exclusively, whereas other participants used primarily the directional mode. There are several possible sources of this variability. First, persons with impaired hearing likely vary in their ability to make use of the directional processing. Consistent with this view, laboratory studies have shown that directional benefit varies significantly across listeners (Ricketts and Mueller, 2000). Notably, Cord et al (2004) found that the size of the directional advantage obtained in a laboratory setting had little predictive relationship with success in everyday listening with directional microphone technology.

Another possible source of variability in the use of the directional mode among participants is that they may have varied in their understanding of the environmental conditions that would favor either program #1 or program #2 use. If some participants did not learn when it was appropriate to activate one mode or the other, they may have simply relied on one mode and rarely switched to the other. However, such an explanation is inconsistent with the data of Cord et al (2002), as well as the similarity in this study of the average use of the directional mode (38.2%) with the average active listening time in listening environments in which directional processing should be effective (34.5%). Further, that the default setting did not seem to have a major influence on the use pattern of the microphone modes argues against the possibility that many of the participants did not discover when to activate the directional mode. For example, the DIR mode was the default setting for the participant who reported using omnidirectional mode 95% of the time. This individual, therefore, appears to prefer the omnidirectional mode in most everyday listening situations that he encounters. This interpretation is consistent with his use of the omnidirectional mode 90% of the time with his own hearing aids.

Another possible cause of the variability in microphone mode use pattern across participants is individual differences in the influence of the environmental variables on microphone performance. If, for example, the patient's audiogram significantly affected the influence of background noise, signal location, and so forth on microphone mode performance, variability in their use pattern could result. It seems unlikely, however, that this might explain most of the variability. First, the participants in this study were relatively homogeneous in terms of standard audiometric variables. Further, Ricketts and Mueller (2000) did not find a predictive relationship between audiometric variables and the magnitude of the directional advantage in a test booth environment.

Clearly, some patients encounter listening situations in which directional microphones should provide a performance advantage more often than other patients. Such differences in everyday listening environments should also result in variability in microphone use. Although it certainly can be argued that directional microphones benefit patients who use them infrequently but appropriately, patients who frequently encounter listening environments where directional microphones can function effectively should profit more from this technology.

It should be noted that a single make and model hearing aid, utilizing a specific type of directional processing (adaptive directionality), was utilized in this study. Ricketts (2000) showed that all commercially available directional hearing aids do not perform the same. Consequently, some specific differences in results might be expected, should the study be repeated with different instruments. It seems likely, however, that the general effects of the environmental variables discussed here would be similar across a variety of current directional technology. Finally, although the results of this study provide insight into the performance of directional processing in everyday listening environments, the effects of other signal processing techniques, such as noise cancellation, require similar study.

CONCLUSIONS

The results of this study suggest that, for the average adult with impaired hearing, the majority of active listening time in daily living is in the presence of background noise. Additionally, the vast majority of daily listening time is typically with the signal source located in front of and relatively close to the listener, and with the background noise source spatially separated from the signal source, that is, not coming from the same location in the listening environment. Each of these environmental conditions should be conducive to effective directional microphone signal processing. With current directional microphone technology, the directional mode should be activated when background noise is present and the signal source is located in front of and is within approximately ten feet of the listener. For the typical adult, this will constitute about one-third of all active listening time. Under other environmental conditions, the omnidirectional mode should be used. Performance in some noisy listening environments will not improve significantly from the processing provided by current directional microphone hearing aids. These typically involve listening with the signal source located at a distance and in the presence of high levels of reverberation.

Although these general guidelines may provide a useful strategy for setting switchable omnidirectional/directional hearing aids in the preferred microphone mode, there will be instances where they will not result in the preferred microphone setting. Even for PLS where statistically significant differences were observed between the two microphone modes, preferences for both microphone modes occurred (see Figure 8). Following these guidelines should increase the likelihood that the hearing aid will be set in the preferred mode; however, it does not insure it. Hence, when less than satisfactory performance is obtained, patients should be encouraged to switch microphone modes.

Considerable variability exists across individuals in the listening environments frequently encountered and the improvement in speech understanding in noise that is obtained from a given amount of directional processing. It is also likely that the opportunity and/or willingness to change difficult listening situations to favor directional microphones vary across individuals. Therefore, these factors should be assessed clinically to determine the potential benefit of directional microphone technology for individual patients.

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NOTES

1. Although participants completed logs only one-third of each day over a three-week period, this analysis describes the average number of minutes per day accounted for by the logs as if participants recorded their active listening encounters in seven full days.

2. Statistical tests were conducted with alpha set to .10, rather than the more traditional .05 level of significance. Although this is a less stringent statistical test in terms of Type I error (i.e., concluding that a distribution is significantly different from the overall distribution when it is not), it reduces the likelihood of a Type II error (i.e., concluding that a distribution is the same as the overall distribution, when a significant difference exists).

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APPENDIX

Everyday Listening Situations within Each PLS

PLS1 (BN Present, Signal Front, Signal Near, Reverberation Low, BN Location Other)

1. Listening to music on radio while driving car.
2. Ordering food at McDonald's drive-through window.
3. Talking with coworker in parking lot.

PLS2 (BN Present, Signal Front, Signal Near, Reverberation Low, BN Location Front)

1. Helping wife on computer.
2. Seated in car, talking to someone out the car window.
3. Meeting with coworkers in computer area; seated with back to wall.

PLS3 (BN Present, Signal Front, Signal Near, Reverberation High, BN Location Other)

1. Talking with friend in subway station.
2. Talking with gym instructor in gymnasium.
3. Talking with clerk at large home-improvement store.

PLS4 (BN Present, Signal Front, Signal Near, Reverberation High, BN Location Front)

1. Having blood drawn in blood lab; seated with back to wall.
2. Talking with coworker in small, uncarpeted office; noise from hallway behind coworker.
3. Talking to motel desk clerk, printer running behind her.

PLS5 (BN Present, Signal Front, Signal Far, Reverberation Low, BN Location Other)

1. Talking to someone on busy city street (traffic noise).
2. Husband reading out loud from across the room with TV on.
3. Talking with merchant at farmer's market.

PLS6 (BN Present, Signal Front, Signal Far, Reverberation Low, BN Location Front)

None

PLS7 (BN Present, Signal Front, Signal Far, Reverberation High, BN Location Other)

1. Trying to hear person in a crowded golf course clubhouse before a tournament.
2. Listening to minister during church reception.
3. Talking with person at the laundromat.

PLS8 (BN Present, Signal Front, Signal Far, Reverberation High, BN Location Front)

1. Watching TV on kitchen counter and conversing with wife in kitchen while having breakfast at kitchen table.
2. Talking with waiter in restaurant, seated with back to wall.
3. Listening for number to be called in busy hospital pharmacy.

PLS9 (BN Present, Signal Other, Signal Near, Reverberation Low, BN Location Other)

1. Driving car while in conversation with three family members.
2. Conversation seated next to friend while riding on subway train.
3. Monitoring computers and phones at work while listening to TV.

PLS10 (BN Present, Signal Other, Signal Near, Reverberation Low, BN Location Front)

1. Conversation seated beside husband on bench with back to wall, while waiting outside car inspection station.
2. Driving car and talking with passenger in front seat, radio on.
3. At softball game, talking with other spectators.

PLS11 (BN Present, Signal Other, Signal Near, Reverberation High, BN Location Other)

1. Conversation with family member at a Chuck E. Cheese restaurant.
2. Bridge party with 12 people.
3. In barber shop, talking with barber while having hair cut.

PLS12 (BN Present, Signal Other, Signal Near, Reverberation High, BN Location Front)

1. Lion's Club meeting—presiding over meeting and listening to speaker while seated facing audience.

2. In kitchen washing dishes, wife talking from behind.
3. Listening to radio while working at computer in basement study.

PLS13 (BN Present, Signal Other, Signal Far, Reverberation Low, BN Location Other)

1. Listening to nature sounds in arboretum with people walking around.
2. Talking to husband while working in yard with dog barking next door.
3. On golf course with three friends.

PLS14 (BN Present, Signal Other, Signal Far, Reverberation Low, BN Location Front)

1. Three-way conversation in driveway; one person in car with engine running.
2. Seated at a large conference table; several people talking at once.

PLS15 (BN Present, Signal Other, Signal Far, Reverberation High, BN Location Other)

1. Cleaning up kitchen while discussing the day's plans with family.
2. In kitchen washing dishes and listening to TV in next room.
3. Listening to the radio while cleaning the basement.

PLS16 (BN Present, Signal Other, Signal Far, Reverberation High, BN Location Front)

None

PLS17 (BN Absent, Signal Front, Signal Near, Reverberation Low)

1. Listening to music CD on computer while reading e-mail.
2. Having dinner at home with wife.
3. Watching a movie on TV in living room.

PLS18 (BN Absent, Signal Front, Signal Near, Reverberation High)

1. Listening to teacher in Spanish class with two other students.
2. Speaking with veterinarian at animal clinic.
3. Conversation with doctor in examination room.

PLS19 (BN Absent, Signal Front, Signal Far, Reverberation Low)

1. Conversation with family member at the park.
2. Talking with wife seated across the living room.
3. Talking with friend on practice green at golf course.

PLS20 (BN Absent, Signal Front, Signal Far, Reverberation High)

1. Talking to spouse in basement.
2. Listening to minister during church service.
3. Listening to string quartet in auditorium.

PLS21 (BN Absent, Signal Other, Signal Near, Reverberation Low)

1. Talking with two family members on patio.
2. Driving car and listening to conversation between spouse and friend.
3. Overhearing conversation in doctor's waiting room.

PLS22 (BN Absent, Signal Other, Signal Near, Reverberation High)

1. In kitchen looking out window, wife talking from behind.
2. Searching for something in basement with wife.
3. Conversation with wife while both moving about kitchen.

PLS23 (BN Absent, Signal Other, Signal Far, Reverberation Low)

1. Talking with wife from another room in the house.
2. Playing golf with three friends.
3. Listening to sounds of nature while working in garden.

PLS24 (BN Absent, Signal Other, Signal Far, Reverberation High)

1. Cooking breakfast and talking with wife seated at kitchen table.
2. Listening to talker at meeting with 20 attendees while seated at large rectangular table.
3. Listening to choir and organ in church balcony.