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The Robustness of Hearing Aid Microphone Preferences in Everyday Listening Environments

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Abstract

Automatic directionality algorithms currently implemented in hearing aids assume that hearing-impaired persons with similar hearing losses will prefer the same microphone processing mode in a specific everyday listening environment. The purpose of this study was to evaluate the robustness of microphone preferences in everyday listening. Two hearing-impaired persons made microphone preference judgments (omnidirectional preferred, directional preferred, no preference) in a variety of everyday listening situations. Simultaneously, these acoustic environments were recorded through the omnidirectional and directional microphone processing modes. The acoustic recordings were later presented in a laboratory setting for microphone preferences to the original two listeners and other listeners who differed in hearing ability and experience with directional microphone processing. The original two listeners were able to replicate their live microphone preferences in the laboratory with a high degree of accuracy. This suggests that the basis of the original live microphone preferences were largely represented in the acoustic recordings. Other hearing-impaired and normal-hearing participants who listened to the environmental recordings also accurately replicated the original live omnidirectional preferences; however, directional preferences were not as robust across the listeners. When the laboratory rating did not replicate the live directional microphone preference, listeners almost always expressed no preference for either microphone mode. Hence, a preference for omnidirectional processing was rarely expressed by any of the participants to recorded sites where directional processing had been preferred as a live judgment and vice versa. These results are interpreted to provide little basis for customizing automatic directionality algorithms for individual patients. The implications of these findings for hearing aid design are discussed.

Key Words: Directional microphones, everyday listening environments, hearing aids, microphone preference

Abbreviations: AD = automatic directionality; BTE = behind the ear; DA = directional advantage; DIR = directional; DNR = digital noise reduction; HI = hearing impaired; IEEE = Institute of Electrical and Electronic Engineers; NH = normal hearing; OMNI = omnidirectional; SNR = signal-to-noise ratio; WDRC = wide dynamic range compression

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Sumario

Los algoritmos automáticos de direccionalidad actualmente implementados en auxiliares auditivos asumen que las personas hipoacúsicas con pérdidas similares preferirán el mismo modo de procesamiento del micrófono en los ambientes cotidianos específicos de escucha. El propósito de este estudio fue evaluar la firmeza de las preferencias de micrófonos para la audición cotidiana. Dos personas hipoacúsicas establecieron juicios de preferencia en cuanto a los micrófonos (preferencia omnidireccional, preferencia direccional, sin preferencia) en una variedad de situaciones cotidianas de escucha. Simultáneamente, estos ambientes acústicos fueron registrados a través de modos omnidireccionales y direccionales de procesamiento del micrófono. Las grabaciones acústicas fueron luego presentadas en un contexto de laboratorio para preferencias del micrófono a los dos sujetos originales y a dos sujetos que diferían en su habilidad auditiva y en su experiencia con procesamiento direccional de micrófonos. Los dos sujetos originales pudieron replicar en el laboratorio sus preferencias de micrófono en vivo con un alto grado de exactitud. Esto sugiere que las bases para la preferencia original y aquella en vivo de los micrófonos fueron correctamente representadas en los registros acústicos. Otros participantes con hipoacusia y normoyentes que escucharon los registros ambientales también replicaron con exactitud las preferencias omnidireccionales originales en vivo; sin embargo, las preferencias direccionales no fueron tan consistentes entre todos ellos. Cuando la clasificación de laboratorio no replicó la preferencia direccional de micrófono en vivo, los sujetos casi siempre dejaron de expresar preferencia por ningún modo de micrófono. Por lo tanto, la preferencia para procesamiento omnidireccional raramente fue escogida por ninguno de los participantes para situaciones donde se había preferido el registro direccional como un juicio en vivo y viceversa. Se interpreta que estos resultados aportan poco en la búsqueda de adecuar automáticamente los algoritmos de direccionalidad para pacientes individuales. Se discuten las implicaciones de estos hallazgos en el diseño de auxiliares auditivos.

Palabras Clave: Micrófonos direccionales, ambientes cotidianos de escucha, auxiliares auditivos, preferencia de micrófonos

Abreviaturas: AD = direccionalidad automática; BTE = retroauricular; DA = ventaja direccional; DIR = direccional; DNR = reducciones digitales de ruido; HI = hipoacúsico; IEEE = Instituto de Ingeniero Eléctricos y Electrónicos; NH = audición normal; OMNI = omnidireccional; SNR = Tasa señal-ruido; WDRC = compresión de rango dinámico amplio

Traditionally, hearing aids have been fit to the hearing loss of the patient, without regard to his or her everyday listening environments. Prescriptive formulas, for example, may use the patient's pure-tone thresholds and loudness judgments to calculate target gain and frequency response. Once set, these amplification parameters are applied to all listening. The advent of multimemory hearing aids allowed different amplification characteristics to be applied in different listening environments. Hence, one set of amplification characteristics might be used when listening to speech in quiet, another set in noisy listening situations, and a third when listening to music. However, such multimemory hearing aids require the user to switch manually among the various memories as the listening environment changes. Manually switchable omnidirectional/directional hearing aids are a version of this technology. Here, the user switches between the two microphone modes, depending upon whether omnidirectional or directional sound processing seems preferable.

One of the primary advantages of advanced-technology digital hearing aids is the potential for the signal processing to change with the acoustic characteristics of the listening situation. These devices are capable of automatically altering amplification characteristics based on an acoustic analysis of the listening environment. Among the earliest examples of this interactive technology, implemented in analog hearing aids, were output-limiting compression and adaptive filtering. Here, the gain and frequency response of the device could be altered based primarily on the input level. More recently, increasingly sophisticated signal processing algorithms have been developed that alter amplification parameters based on more complex analyses of the acoustic environment. Most of these algorithms are designed to deal with the interfering effects of background noise. Predominant among these are digital noise reduction (DNR) and automatic directionality (AD). In DNR, the gain is selectively reduced across the frequency spectrum when noise is present. In AD, omnidirectional or directional microphone processing is activated based on, among other factors, the presence of background noise in the environment. Although manufacturers have achieved some success with their DNR and AD circuitry, the efficacy of these automatic processing schemes, especially in everyday listening, has not been definitively established to date.

Manufacturers have taken differing signal processing approaches to both DNR and AD. Algorithms differ from manufacturer to manufacturer depending on assumptions about the optimal amplification characteristics in a particular listening environment, as well as the capabilities of the signal processors. For the most part, however, these algorithms assume that the preferred signal processing in a particular acoustic environment is relatively constant across hearing-impaired (HI) listeners. For example, AD algorithms that switch microphone modes (based on an acoustic analysis of the listening environment) assume that directional processing will be preferred in a particular everyday listening environment by virtually all hearing-aid users. This assumption, however, appears to be largely untested. Walden et al (2004) examined preferences for omnidirectional and directional microphone processing in a group of HI persons across a large number of everyday listening situations. Although listeners tended to prefer one processing mode to the other in similar everyday listening situations, substantial individual variability was observed. In any case, these data do not provide a definitive test of the assumption that different listeners have similar microphone preferences because, although the listening environments that were compared in that study were similar in their general characteristics, microphone preferences were not obtained by different patients in identical listening environments. It remains possible that the signal processing (e.g., microphone mode) preferred by one listener in a specific listening environment may not be preferred by other listeners.

If there is substantial individual variability in the preferred signal processing for a given listening situation, the same processing algorithm cannot be effectively applied to all hearing aid users. Obviously, this adds considerably to the complexity of developing successful adaptive (automatic) hearing aid signal processing. Given substantial variability, it may be necessary to program signal processing algorithms, such as DNR and AD, to the requirements of the individual patient. This might be accomplished via learning algorithms that take input from the hearing aid wearer during normal daily use to determine preferred signal processing characteristics across a variety of everyday listening environments (Walden et al, 2005). However, more simple solutions to automatic signal processing strategies such as DNR and AD can be pursued if the same signal processing is generally preferred across listeners for a given acoustic environment.

Another factor adding to the complexity of effective advanced signal processing algorithms is the influence of nonacoustic factors in listener preferences. For example, AD algorithms assume that the basis of the individual's preference for omnidirectional versus directional processing is manifest in the acoustic input. However, nonacoustic factors can be important. For example, if a listener wishes to attend to a talker who is located to the side or behind, and to ignore a talker who is in front, directional processing (which might otherwise be preferred) will serve as a detriment to hearing the desired talker. Clearly, the listener's intent is not represented in the acoustic input.

Yet another issue that could complicate automatic signal processing in hearing aids, which is related to the general issue of individual variability in listener preferences, is how and where the signal should be sampled. The acoustic signal that is delivered to the patient's tympanic membrane can differ from the output of the digital signal processor due to earmold and ear canal effects. If these acoustic alterations of the DSP output are sufficient to change listener preferences, effective adaptive signal processing may require that the acoustic output of the hearing aid be sampled and delivered back to the digital signal processor, resulting in further design complications.

This study is a preliminary exploration of the issues discussed above, focusing on the robustness of omnidirectional versus directional microphone preferences in everyday listening. Specifically, we wished to determine the extent to which microphone preferences from everyday listening environments are stable across listeners, and whether the recorded output of the hearing aid signal processor can be used to replicate actual live microphone preferences obtained in everyday listening. Two HI listeners who were highly experienced with the hearing aid and test methodologies used in this study made microphone preference judgments in everyday listening situations while wearing a manually switchable omnidirectional/directional hearing aid. Simultaneously, the output of the digital signal processor (sampled prior to transduction by the receiver) was recorded through each microphone mode. These recordings were later presented in a laboratory setting to the original listeners, as well as other groups of HI and normal-hearing (NH) listeners, to obtain microphone preferences. The original live microphone preferences were compared to those obtained by the different listening groups to determine the robustness of the preferences across a range of everyday listening situations.

METHOD

Participants

Participants included 30 persons with impaired hearing, recruited from the patient population of the Army Audiology and Speech Center, and 10 normal-hearing participants. All HI participants had bilateral, generally symmetric hearing impairments that fell within the fitting range of the test hearing aid used in the study. The general requirements for participation were sensorineural hearing loss (cochlear site of lesion), which was verified by differences between air- and bone-conduction thresholds of 10 dB or less and by normal tympanograms (Type A; Jerger, 1970); presence of ipsilateral acoustic reflexes for a 1000 Hz tone; and unaided monosyllabic word-recognition ability in quiet (NU-6) of 50% or better in each ear at a comfortable listening level. Although all testing in this study was performed unilaterally, pure-tone thresholds were within 30 dB between ears at each test frequency from .25 to 6 kHz, with the three-frequency average (.5, 1, 2 kHz) differing between ears by no more than 13 dB for any participant.

All HI participants reported regular use of binaural hearing aids for a minimum of four hours per day. Furthermore, if their own hearing aids had a manually switchable directional microphone option, they reported regular, selective use of each microphone option in everyday listening. Finally, all HI participants were screened with a test of speech recognition in noise (see below) while wearing the test instrument to make sure that they obtained a directional advantage (DA) of at least 15%.

Two HI persons from the 17 participants in Walden et al (2004) were selected to serve as *field raters* of microphone preferences. Their selection was based, in part, on a close match of their hearing thresholds to the mean audiogram of the participants in that study, which was used to program the test hearing aid in this study. Further, they had considerable experience with the test hearing aid and methodologies used in this study and were regarded as highly cooperative and reliable subjects based on their participation in the earlier study. Each field rater participated in three phases of the study, which required a total of four clinic visits. First, each identified two everyday listening environments in which he preferred omnidirectional microphone processing, two in which he preferred directional processing, and two in which he had no preference. Hence, live field microphone ratings were obtained in a total of 12 everyday listening situations (2 environments X 3 microphone preferences X 2 field raters). These preferences were obtained with the test instrument programmed to the mean audiogram of the 17 participants (34 ears) in the earlier study, with a minor (-3 dB) gain reduction for both field raters based on their hearing threshold at 1 kHz. Secondly, simultaneous with their field microphone preferences, the field raters took part in recordings of the 12 acoustic environments through the test hearing aid. Details of the recording procedures are described below. Finally, approximately three months later, both individuals provided microphone preference ratings in a laboratory setting to the (edited) recordings from the field environments.

Field Rater 1 was a 76-year-old man who had used hearing aids for about 12 years and reported an average 12 hours of daily use. He had a mild-to-moderate, gradually sloping, sensorineural hearing loss with word recognition in quiet in the test ear of 88% (NU-6 test). Field Rater 2 was an 85-year-old man. He had used hearing aids for about five years and reported 17 hours of daily use. He also had a gradually sloping, sensorineural hearing loss with word recognition in the test ear of 96%. The right ear was selected as the test ear for Field Rater 1 and the left ear for Field Rater 2. Figure 1 shows the audiogram for the test ear of each field rater, as well as the mean bilateral audiogram for the 17 participants (34 ears) in the earlier study. As can be seen, the three pure-tone audiograms are relatively similar in configuration and degree of loss.

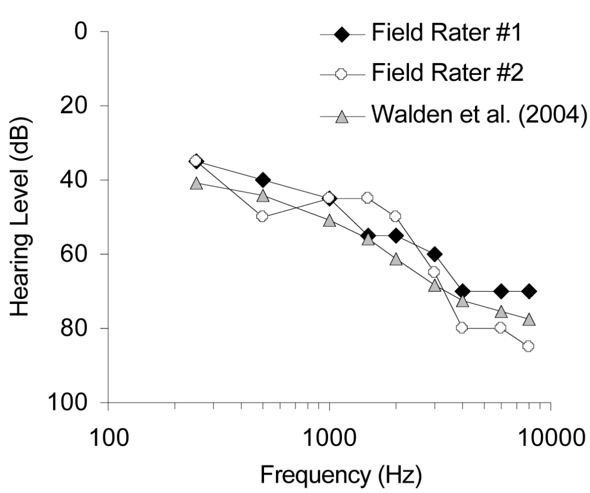

Figure 1. Pure-tone audiogram in test ear of each field rater and mean audiogram of participants in Walden et al (2004).

The other 28 HI participants, as well as the 10 NH participants, took part only in the laboratory portion of the study, which was completed in one session. The HI participants were divided into three groups. The first consisted of eight of the remaining 15 participants in Walden et al (2004). This group will be referred to as the "Cohort" group. All but one were men. At the conclusion of the earlier study, they had been fit bilaterally with the ITE (in-the-ear) version of the hearing aid used in the current study. They had been wearing these instruments on a daily basis for a minimum of 18 months prior to their enrollment in this study, which used the BTE (behind-the-ear) version of their hearing aids. As a result of their participation in the earlier study, these individuals had extensive experience with the test instrument, had demonstrated a DA ≥15 dB with this hearing aid in laboratory testing, and had extensive experience making omnidirectional/directional microphone preference judgments in everyday listening situations.

The remaining 20 HI participants were experienced hearing aid wearers who had not previously served in a hearing aid study. The second group, hereafter the "Omni" group, consisted of nine men and one woman. They had been fit bilaterally with hearing aids having only omnidirectional microphones (i.e., no directional option) within the three years preceding their enrollment in this study. The third group, hereafter the "Dir" group, consisted of ten men who had been fit bilaterally with manually switchable omnidirectonal/directional hearing aids within the three years preceding their enrollment and who routinely used both microphone modes in daily living. Finally, the 10 NH participants (3 men, 7 women) had air-conduction thresholds within normal limits (≤15 dB HL) from .25 to 6 kHz and reported no abnormal hearing symptoms.

Laboratory testing was administered

unilaterally. For the HI participants, the test ear was selected depending on which ear provided the closest match to the mean audiogram used to program the test hearing aid. Often, little difference existed between ears. In these cases, participants were allowed to select their preferred ear, as were the NH participants. The field raters listened through the ear that had been selected for the live field testing. For the remaining 38 participants, 23 listened through their right ear and 15 through their left ear. The mean audiograms (test ears) of the participants in the Cohort, Omni, and Dir groups are shown in Figure 2. Also shown (lines without symbols) are the threshold minima and the maxima for these 28 HI participants at each test frequency. All audiograms fit within the fitting range of the test hearing aid. On average, the participants in the three HI groups had moderate-to-severe, gradually sloping hearing losses comparable to those of the field raters. Audiometric thresholds for the three HI groups were compared using a two-way ANOVA with group and frequency as factors. The results showed a significant group effect ($F = 12.99$, $p < 0.001$) and, as expected, a significant frequency effect ($F = 50.86$, $p < 0.001$). However, the group X frequency interaction was not significant ($F = 1.41$, $p = 0.14$). The Tukey HSD procedure indicated that all three means were significantly different from one another. The Cohort group had the poorest hearing and the Dir group the best hearing, particularly in the low-frequency region, among the three HI groups.

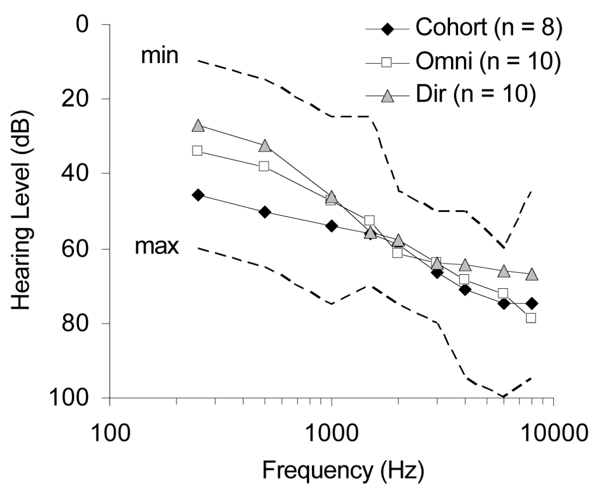

Figure 2. Mean audiogram for the test ear of participants in each HI group. The lines without symbols show the minimum and maximum pure-tone threshold obtained at each test frequency across the HI participants.

The three HI participant groups were also compared for speech recognition scores. Mean NU-6 word recognition in quiet under earphones (test ear) at a comfortable listening level was 79.8% (SD = 15.5, range = 56–100) for Cohort group, 86.6% (SD = 9.7, range = 72–100) for Omni group, and 86.6% (SD = 9.7, range = 72–100) for Dir group. A one-way ANOVA revealed that the groups were not significantly different ($F = 0.95$; $p = 0.40$) on this measure.

Demographic data for the four participant groups are presented in Table 1. The mean age of the three HI groups did not differ significantly, although the mean age of the NH group was significantly younger than each of the three HI groups (ANOVA: $F = 34.60$, $p < 0.001$). A one-way ANOVA comparing total hearing aid use (in years) revealed a statistically significant difference among the groups ($F = 4.66$, $p < 0.05$). Comparison of the means (Tukey HSD procedure) indicated that the Cohort group had used hearing aids for a significantly longer period of time on average than the other two groups, which probably reflects their greater and, presumably, more long-standing hearing losses. Total hearing aid use did not differ significantly between the Omni and Dir groups. Finally, a statistical comparison of daily hearing aid use (hours per day) revealed a significant group effect ($F = 4.44$, $p < 0.05$). The Omni group used their hearing aids significantly less on a daily basis than the other two groups,

Table 1. Demographic Data (mean and range) for the Four Groups of Participants

Group	Age (years)	Hearing Aid Use (years)	Daily Use (hours)
Cohort	74.5 (61–85)	14.3 (5–29)	15.6 (14–17)
Omni	72.7 (60–82)	7.3 (2–14)	10.8 (4–16)
Dir	72.7 (63–78)	6.5 (3–10)	13.3 (8–18)
NH	41.3 (27–66)	NA	NA

although the Cohort and Dir groups did not differ significantly. One might expect that the Dir group, with better hearing, would use their hearing aids less than the Omni group. However, it is possible that the choice of directional hearing aids led to greater hearing aid satisfaction and use as has been reported by Kochkin (2003).

Test Hearing Aid

A GN ReSound Canta 770D BTE hearing aid was used in the study. It is a multiband, multimemory digital hearing aid with variable wide dynamic range compression (WDRC) and no user-adjustable volume control. Directionality is achieved electronically via a two-microphone system and includes an adaptive polar response option. Although this option was activated throughout the study, the Canta770D defaults to a hypercardioid polar response in relatively diffuse background noise, which appears typical of most everyday noisy listening situations (Walden et al, 2004). Unvented, custom earmolds were made for the two field raters and were used during the field testing. For the remaining 28 HI participants who did not take part in the field portion of the study, the test hearing aid was used only for screening DA, and the device was coupled to the ear via a foam ear tip.

The first two memories of the test hearing aid were programmed with the manufacturer's "basic program." The standard omnidirectional microphone mode was programmed into one of the two memories and the directional mode into the other (hereafter, referred to as the "OMNI" and "DIR" programs, respectively) in counterbalanced order across the participants. A push button on the back of the instrument allows the wearer to switch between programs. The appropriate number of audible tones informs the user whether program 1 or program 2 has been activated.

The hearing aid was fit according to the manufacturer's "Audiogram Plus" fitting algorithm with full compensation for the normal low-frequency roll-off in the directional mode ("Max Boost"). No noise reduction was used in either program, and digital feedback suppression was not required in any of the fittings.

Participants were not informed of the specific nature of the signal processing provided by the two programs; that is, they were not told that one of the programs provided omnidirectional- and the other directional-microphone processing. Rather, they were simply told that the two programs were "different ways of processing sound."

As previously noted, the bilateral average audiogram of the 17 participants (34 ears) in the previous study (Walden et al, 2004) was used to program the study instrument (Figure 1). However, because thresholds at 1000 Hz for the 30 HI participants ranged from 25 to 75 dB HL, overall gain was adjusted to prescribed gain at 1000 Hz based on each participant's audiogram in the test ear. As a result, the gain adjustment at 1000 Hz ranged from -10 to 15 dB, although the compression settings for the various frequency bands were held constant across the 30 HI participants. Because the two field raters had the same threshold at 1000 Hz, the field measures were made with the identical hearing aid program.

Mean frequency responses (for the 30 fittings) for three input levels of speech-weighted noise (50, 65, and 80 dB SPL) are shown in Figure 3. The 2-cc coupler measurements (Fonix 6500-CX) were made in the OMNI mode and show the characteristic decrease in gain with increasing input level of WDRC. The mean frequency response was also obtained in the DIR mode with the 65 dB SPL input (displayed in Figure 3 as one of the two middle and

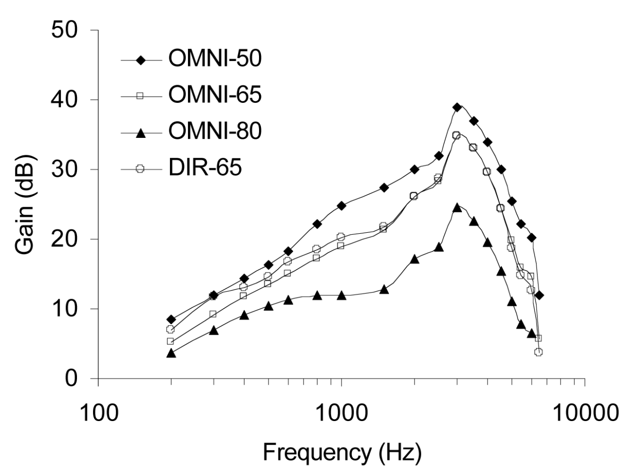

Figure 3. Mean 2-cc coupler gain of the test instrument for three input levels (50, 65, 80 dB SPL) in the OMNI mode and for a 65 dB SPL input in the DIR mode.

overlapping curves) to assure that the frequency-gain characteristics of the OMNI and DIR programs were equalized. As is apparent, the mean frequency responses of the two programs were nearly identical. At the end of the study, the coupler responses of the hearing aid in the OMNI mode and in the DIR mode were compared using the method suggested by Frye (2006) to verify directionality. The results indicated that the average directional effect in the .5–6 kHz range was 5.9 dB.

Screening for Directional Advantage

A test of speech recognition was administered to verify that each of the 30 HI participants obtained a DA of at least 15% under laboratory test conditions. The test hearing aid was fit to the test ear using a foam ear tip, and the opposite ear was plugged with a foam earplug. With the listener seated comfortably in a sound-treated test booth, IEEE sentences (Institute of Electrical and Electronic Engineers, 1969) were presented at 65 dBA from an ear-level loudspeaker at 0° azimuth. Each sentence contains five key words that form the basis for scoring (percent correct). Simultaneously, uncorrelated speech-shaped noise was introduced from three ear-level loudspeakers at 90°, 180°, and 270° azimuths with a combined level of 65 dBA, thereby creating a 0 dB signal-to-noise ratio at the location of the participant's head. The participant was asked to repeat each word of the sentence and to guess when unsure. Two ten-sentence lists were presented for the omnidirectional mode and two for the directional mode (100 key words each), with the order of presentation of the two test conditions counterbalanced in ten-sentence lists across participants. If the performance level of the listener was below 20% for the first list of 50 test words in either mode, the signal-to-noise ratio was adjusted to +3 or +6 dB by reducing the noise level, and testing began anew with different test lists. The DA was calculated as the percent of words correctly recognized for the omnidirectional mode subtracted from the percent of words correctly recognized for the directional mode.

Identification of Field Recording Sites

During their second visit, the two field raters were fit unilaterally with the test hearing aid using their custom earmolds. The opposite ear was occluded with a foam earplug. Each field rater was required to identify six noisy everyday listening environments, two in which he distinctly preferred omnidirectional processing, two in which he distinctly preferred directional processing, and two in which he had no clear preference for either microphone mode. Each field rater walked around the Walter Reed campus in search of appropriate listening environments, accompanied by two of the investigators. As criteria for inclusion, noise was present in every listening environment, and speech was the primary signal. Given that these field judgments were to serve as "gold standard" microphone preferences for the laboratory ratings, great care was taken to assure that the field microphone preferences were constant and unequivocal. Acoustically stable listening environments were required to allow thorough comparisons between the two microphone modes, both in the field and for the laboratory ratings. To facilitate this, one or more of seven adults (four men and three women) variously accompanied the field rater and investigators to serve as the primary talker in each listening environment, reciting narrative speech. Identification of appropriate listening situations was largely by trial and error as the primary talker and/or the field rater slowly moved around in the listening environment until one of the three preferences (Program 1, Program 2, No Preference) clearly emerged. Location and distance of the primary talker relative to the listener were the most distinct variables determining microphone preferences. The level of the background noise (e.g., fans, crowds of people, music from a radio, sounds of nature, traffic) varied considerably across the different environments.

Once a stable environment was located and the listener had indicated his microphone preference, a 2 min recording was made through the hearing aid. During this recording period, the distance and orientation between the primary talker and the field rater were held constant. Details of the recording method are provided below.

At the end of the recording, the field rater was asked to confirm that the microphone preference had not changed, and a modified Hearing Aid Use Log (Walden et al, 2004) was filled out by one of the investigators, documenting the field rater's microphone preference and describing the listening environment using a checklist format (see Appendix 1).

Table 2 describes the talker location and distance, and background noise location and perceived loudness, for the 12 listening environments. The first two listening environments listed under each microphone preference category are those of Field Rater 1, and the last two are from Field Rater 2. In general, there was relatively good agreement between the two field raters regarding the characteristics of OMNI-preferred and DIR-preferred listening environments. In each of the four OMNI-preferred sites, the primary talker was located to the side or behind the listener and relatively near (<10 ft). Background noise was located all around or behind the listener, and its perceived level varied from soft to loud.

As expected, the primary talker was in front of the field rater for the four DIR-preferred sites. Further, except for the conference room, the talker was located close to the listener (<3 ft). The background noise was perceived as being all around, with the exception of the conference room where the noise source (i.e., an electric fan) was located behind the listener. The perceived loudness of the background noise varied across these four sites.

In contrast to the OMNI-preferred and DIR-preferred sites, the four no-preference listening environments were more variable in their characteristics across the two field raters. For Field Rater 1, the primary talker

Table 2. Characteristics of the 12 Everyday Listening Environments, Including Location and Distance of the Primary Talker, and Location and Loudness of the Background Noise

	Talker						Background Noise			
	Location			Distance (feet)			Location			
Recording Site	Front	Side	Back	<3	3–10	>10	Front	Back	All Around	Loudness
OMNI-Preferred Sites										
Outdoor Garden			x		x				x	Moderate
Car (passenger)			x	x					x	Soft
Office (10' x 12')		x		x				x		Moderate
Hospital Cafeteria		x		x					x	Loud
DIR-Preferred Sites										
Conference Room (14' x 18')	x					x		x		Moderate
Hospital Cafeteria	x			x					x	Soft
Outside of Hospital	x			x					x	Soft
Hospital Lobby	x			x					x	Loud
No-Preference Sites										
Lunch Room (13' x 15')		x		x			x			Soft
Outdoor Garden		x		x					x	Moderate
Classroom (19' x 25')	x					x	x			Loud
Conference Room (14' x 18')	x				x		x			Soft

was located to the side and relatively close to the listener in both no-preference sites (i.e., break room, outdoor garden), although the characteristics of the noise varied between these two settings. The outdoor garden that yielded an OMNI- preferred rating for Field Rater 1 also yielded a no-preference rating for this listener. A distinct preference for omnidirectional processing resulted when the talker was located directly behind and several feet (but not more than 10 ft) from Field Rater 1. However, when the talker was located to the side and very close (<3 ft), there was no preference for either microphone mode. For Field Rater 2, the primary talker and noise sources were located in front of the listener in both no-preference environments (i.e., classroom, conference room), with a talker-to-listener distance of several feet.

Acoustic Recordings

The test hearing aid was modified by the manufacturer to allow the electrical output signal (i.e., before transduction by the hearing aid receiver) to be accessed directly via an electrical connector attached to the outside of the hearing aid case. Recordings of the acoustic environment were made by feeding the pulse-code modulated output of the signal processor to a demodulator. The demodulated signal was fed to a pre-amplifier and then to the analog-to-digital converter of a notebook computer.

During the 2 min digital recording of each listening environment, the field rater switched between the two microphone modes in 10 sec intervals at the direction of one of the investigators. The one- or two-tone signal produced by the hearing aid as each microphone mode was activated, which identified the processing mode for each 10 sec sample, was also recorded.

Preparation of Laboratory Test Materials

The 2 min recordings of each listening environment consisted of six 10 sec samples of omnidirectional processing interleaved with six 10 sec samples of directional processing. These recordings of the 12 everyday listening environments were edited for use in all subsequent listening tasks. From each of the original 2 min recordings, six overlapping 40 sec samples were produced, thereby creating a total of 72 listening items. The six samples of each environment began at different places in the 2 min recordings such that three started with 10 sec of omnidirectional processing and three began with 10 sec of directional processing. Each 40 sec sample contained two 10 sec samples of omnidirectional processing alternating with two 10 sec samples of directional processing. The tones produced by the hearing aid that indicate which processing mode was activated were digitally moved to correspond with the order of the samples in a specific 40 sec test item. That is to say, a given 40 sec test item did not always begin with omnidirectional or with directional processing, but the tone sequence was always 1-2-1-2.

Laboratory Preference Ratings

Each of the 40 participants listened monaurally to the edited recordings of the listening environments in a sound-treated booth via an insert receiver. Initially, a comfortable listening level was established for each participant, as follows: Concatenated IEEE sentences recorded through the test hearing aid mounted on KEMAR (Burkhard and Sachs, 1975) were presented in quiet through the insert receiver to the listener's test ear. A comfort level was established using a bracketing procedure in 5 dB steps. The participant periodically indicated his or her perceived loudness of the concatenated sentences using a seven-category loudness scale adapted from the contour test of the IHAFF (Independent Hearing Aid Fitting Forum) protocol (Valente and Van Vliet, 1997). The comfort level determined by this procedure was used to present a few practice items (not included in the 72 test items), as well as the actual 72-item test.

The 72 items were presented randomly, without replacement, to each participant. For each item, participants were required to indicate whether they preferred sample 1 (one tone), sample 2 (two tones), or had no preference. Typically, the listeners responded after the second or the third 10 sec portion of the test item; that is, they seldom needed the full 40 sec sample to make a preference judgment. The software identified which sample (1 or 2) was associated with which microphone mode in each 40 sec sample and recorded the participant's responses accordingly. Once a preference response was made to a given item, the test advanced to the next item. Testing time was about 90 min, which included one or two rest periods.

RESULTS

Directional Advantage

As noted earlier, HI participants were required to obtain a DA of 15% or greater with the test hearing aid at 0 dB, +3 dB, or +6 dB SNR (signal-to-noise ratio), as a criterion for enrollment in the study. Five of the participants passed the screening test at 0 dB SNR, 12 passed at +3 dB SNR, and the remaining 13 participants passed at +6 dB SNR. Field Rater 1 obtained a DA of 15% (+3 dB SNR), and the DA for Field Rater 2 was 26% (+6 dB SNR). For the HI groups, the mean DA was 38.4% for the Cohort group (SD: 14.4; range: 19–64), 33.3% for the Omni group (SD: 12.0; range: 18–65), and 31.0% for the Dir group (SD: 9.2; range: 20–47). A one-way ANOVA indicated that the mean DA did not differ significantly among the three HI groups ($F = 0.83$, $p = 0.45$).

Laboratory Preference Ratings

The primary purpose of this study was to determine the extent to which OMNI versus DIR microphone preferences in everyday listening situations are similar across HI persons. Ideally, this would be evaluated by comparing the microphone preferences of a large number of listeners in identical live everyday listening environments. As a practical matter, such a study is difficult to conduct because of the individual and dynamic nature of most everyday listening situations. Not only are everyday listening environments largely unique to an individual, the specific acoustic characteristics of a given listening environment often change considerably over time as, for example, the talker and listener move. This problem was addressed in this study by making acoustic recordings of a variety of everyday listening environments and using those recordings presented in a laboratory setting to evaluate the similarity of microphone preferences across different listeners. Obviously, this approach assumes that the essential determinants of microphone preferences in everyday listening are present in the acoustic signal (captured by the recordings). Notably, the same assumption underlies automatic directionality algorithms. To assess this assumption, the laboratory preference ratings of the two field raters were compared to their actual live microphone preferences.

Intrasubject Agreement

Figure 4 shows the distribution of OMNI-preferred, DIR-preferred, and no-preference ratings (expressed as percentages) obtained from the two field raters during laboratory testing, organized according to their preference categories in the field. Chance performance is 33.3%. Although these data are pooled across specific listening situations in each preference category and combined for the two field raters, they reflect only the degree of agreement of each field rater's laboratory preferences with his own field ratings. Depicted, therefore, is the distribution of 24 laboratory preference ratings within each field preference category (6 samples X 2 sites X 2 field raters). Recall that approximately three months passed between when the field raters made their live preference judgments and when they participated in the laboratory testing. This, combined with the multiple items presented from each field

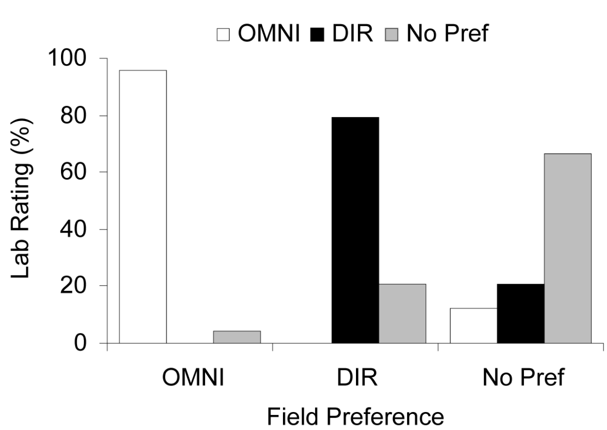

Figure 4. Agreement between the laboratory and field microphone preference ratings for the field raters (intrasubject agreement), pooled across specific listening situations in each preference category.

environment and the random association of the microphone modes with the one or two tones indicating sample order within items on the laboratory test, makes it highly unlikely that memory played a role in the relatively high intrasubject agreement observed. As can be seen, the vast majority of the laboratory ratings given by the field raters agreed with their field preferences. However, the level of agreement varied with the preference category. For OMNI-preferred sites, 23 of the 24 laboratory ratings (95.8%) agreed with the field preference, whereas 19 of the 24 laboratory ratings (79.2%) agreed with the field preference for the DIR-preferred sites. A no-preference rating was given to the other five test items from the DIR-preferred site recordings. For the no-preference sites, 16 of the laboratory ratings (66.7%) agreed with the field preference, with the remaining eight ratings being distributed between OMNI and DIR preferences.

Figure 5 displays the intrasubject agreement separately for each of the four everyday listening environments in each preference category. It should be noted that the data for each environment is the distribution of only six laboratory ratings, so caution should be used in interpreting these data. Nevertheless, it appears that the level of agreement between the laboratory ratings and field preferences differed somewhat among the specific listening environments. For six of the 12 sites, there was perfect agreement between the field and laboratory preference, and for three additional sites, five of the six laboratory ratings agreed with the field preferences. For the remaining three sites, however, good agreement was not observed. Notably, two of these were DIR-preferred sites; specifically, the conference room (Field Rater 1) and outside a building (Field Rater 2). Nevertheless, the intrasubject comparisons (Figures 4 and 5) generally suggest that the determining factors in the OMNI and DIR preferences in the everyday listening environments were largely captured in the acoustic recordings, although this was less true for the DIR preferences than for the OMNI preferences. With this as a frame of reference, it is possible to consider the primary purpose of the study; that is, the consistency of microphone preferences across listeners.

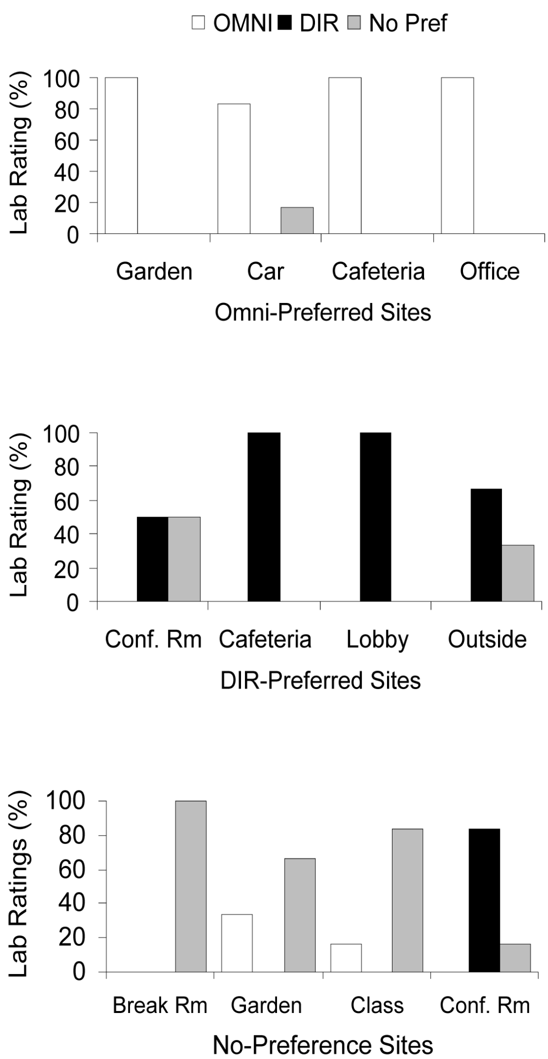

Figure 5. Agreement between the laboratory and field microphone preference ratings for the field raters (intrasubject agreement) for the specific listening situations in each preference category.

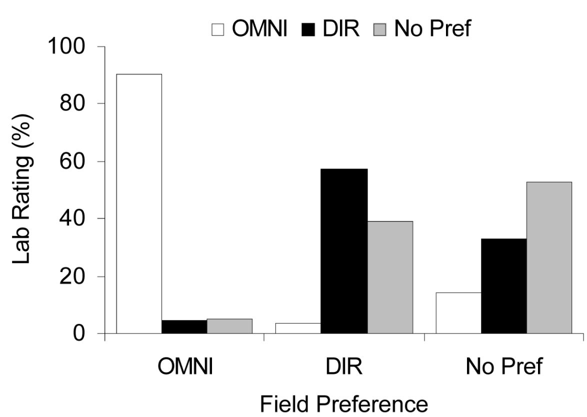

Figure 6. Agreement between the laboratory and field microphone preference ratings for 38 participants (intersubject agreement), pooled across specific listening situations in each preference category.

Intersubject Agreement

Figure 6 shows the distribution of OMNI-preferred, DIR-preferred, and no-preference ratings for the remaining 38 participants, organized according to (field rater) preference category and pooled across specific listening situations within each category. Depicted, therefore, is the distribution of 912 laboratory preference ratings (6 samples X 4 sites X 38 participants) within each field preference category. Overall, these 38 participants tended to agree with one another (and with the field raters' live preferences) in their laboratory preferences. Again, however, the degree of agreement varied with the field preference category, with best agreement (90.4%) being achieved for the OMNI-preferred environments. For the DIR-preferred and no-preference sites, agreement was 57.3% and 52.6%, respectively.

A comparison of the intrasubject agreement data in Figure 4 with the intersubject agreement data in Figure 6 suggests generally similar trends. This observation was confirmed by separate 3 X 2 chi square analyses comparing the data of these two figures for each field preference category. Results were $\chi^2 = 1.18$ ($p = 0.55$), 4.80 ($p = 0.09$), and 2.00 ($p = 0.37$) for the OMNI-preferred, DIR-preferred, and no-preference sites, respectively. Field preferences for OMNI-preferred sites appeared to be highly replicable in the laboratory, both within and across listeners, but less so for the DIR-preferred and no-preference sites. Although the general pattern of results for the DIR-preferred and no-preference sites were similar between the field raters and the other 38 participants, as substantiated by the chi square analyses, the degree of agreement between the field preferences and laboratory ratings for the DIR-preferred sites dropped from nearly 80% for the intrasubject comparisons (Figure 4) to 57% for intersubject comparisons (Figure 6).

Figure 7 displays intersubject agreement for each of the four listening situations in each preference category. Hence, the distribution of 228 laboratory preference ratings (six samples X 38 participants) is depicted for each of the four sites within each panel. Although generally similar patterns of laboratory preference ratings were observed for the four field sites within each preference category, quite different patterns of findings were obtained for the three preference categories. It is evident in the first panel that the laboratory ratings showed excellent agreement (>95%) with the field preference for three of the four OMNI-preferred sites. For the recordings made in a car, agreement was 75.4%, with the other laboratory ratings being divided between DIR-preferred and no preference. These data, therefore, generally support the conclusion that OMNI microphone preferences are highly robust across listeners and listening environments.

For the DIR-preferred sites (second panel), the laboratory ratings showed substantially less agreement, ranging from 43.4% (outside a building) to 65.4% (cafeteria). Laboratory

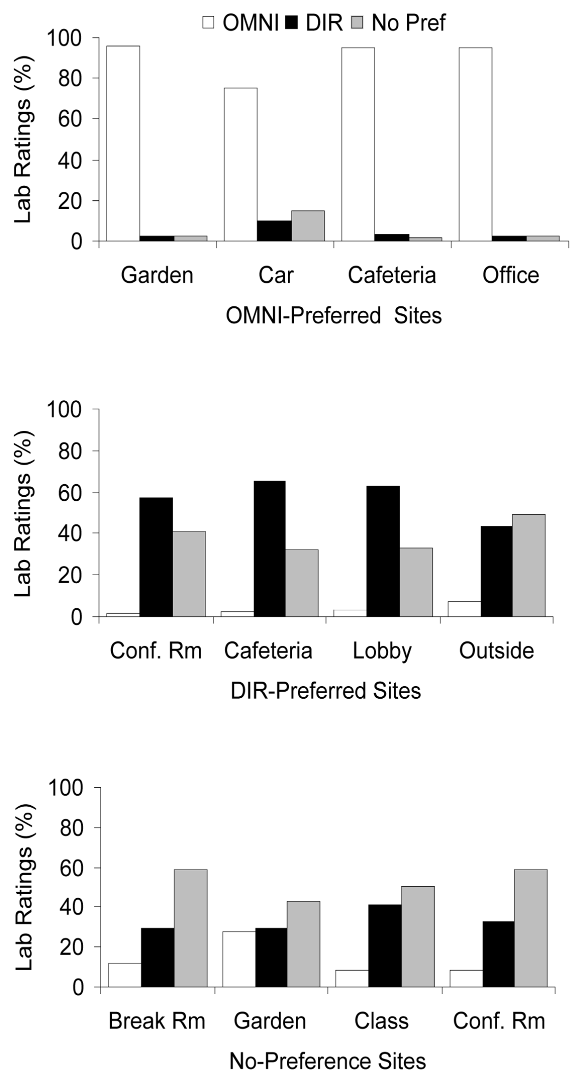

Figure 7. Agreement between the laboratory and field microphone preference ratings for 38 participants (intersubject agreement), for the specific listening situations in each preference category.

ratings that were not in agreement with the DIR field preference were almost always no preference; that is to say, OMNI processing was rarely preferred in the laboratory for a DIR-preferred field site. Notably, for one of the DIR-preferred field sites (outside a building), the majority of the laboratory ratings did not agree with the field preference.

Results for the no-preference field sites (third panel) revealed that a no-preference rating was the most frequent response across all four sites. However, DIR preferences were often obtained in the laboratory for each of these sites and, to a lesser extent, OMNI preferences.

Participant Groups

The data in Figures 6 and 7 suggest that preferences for omnidirectional processing are highly robust across listeners and everyday listening environments. However, this appears to be less true for directional processing. Rather, the field raters' DIR preferences in everyday listening situations were not consistently replicated by the other 38 participants in the laboratory. Often a no-preference rating was assigned to the recorded samples of the DIR-preferred sites. As suggested earlier, part of this inconsistency may be because the acoustic recordings did not always fully reflect why directional processing had been preferred by the field rater in a particular listening environment. However, it is also possible that some of the inconsistency between the laboratory ratings and the field preferences are attributable to participant differences, such as possible effects of hearing loss and experience with hearing aids. This possibility was explored by comparing results for the four participant groups. Recall that the Cohort group, on average, had the greatest amount of hearing loss and the longest history of hearing aid use compared to the other groups. In addition, both the Cohort and Dir groups had experience with directional hearing aids in everyday living in contrast to the Omni group, who had no experience with this type of signal processing prior to their participation in this study. The data for each of the four groups are shown in Figure 8, pooled across listening sites.

Overall, the Cohort and the NH groups appeared to replicate the field preferences most consistently. Not unexpectedly, the OMNI-preferred field preferences were highly replicable in the laboratory for all four participant groups, consistent with earlier representations of the data. This was confirmed by a 3 X 4 chi square analysis of the data for the OMNI-preferred sites,

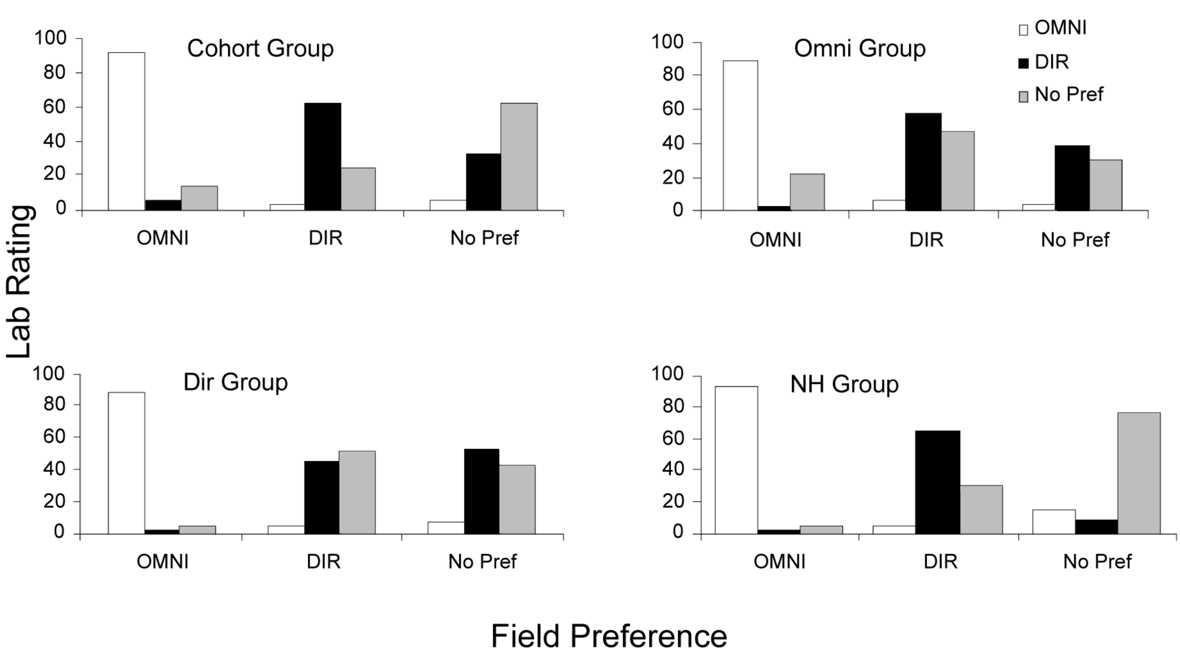

Figure 8. Agreement between the laboratory and field microphone preference ratings pooled across specific listening situations in each preference category for each of four participant groups.

which revealed no significant group differences ($\chi^2 = 8.37$, $p = 0.21$) . The DIR field preferences were less consistently replicated in the laboratory for all groups, but particularly for the Dir group where no-preference ratings were the most frequent response. A 3 X 4 chi square analysis of the data for DIR-preferred sites revealed that the group differences were highly significant ($\chi^2 = 34.36$, $p < 0.001$). Similarly, the response patterns for the no-preference sites were significantly different ($\chi^2 = 167.48$, $p < 0.001$) among the participant groups. Although the NH group replicated the no-preference field preferences with a relatively high degree of consistency (76.3%), the Omni and Dir groups more frequently preferred the directional processing for these listening environments based on the laboratory recordings.

Differences among the four participant groups are summarized in Figure 9, which shows the percent agreement between the laboratory rating and the field preference for each of the four groups. These data were compared using a two-way ANOVA with participant group and field preference category as factors. As expected, the main effect for preference category was highly significant ($F = 41.48$, $p < 0.001$). Agreement between the field and laboratory preferences was significantly higher for the OMNI-preferred sites. However, the main effect for group was not significant ($F = 2.24$, $p = 0.08$). Although, overall, the four groups did not differ significantly from one another, a significant group X preference category interaction was observed ($F = 2.55$, $p < 0.05$). As noted earlier, there appeared to be some tendency for the Cohort and NH groups to show slightly greater agreement with the field ratings than the Omni and Dir groups, although this was mainly attributable to the data for the no-preference field sites.

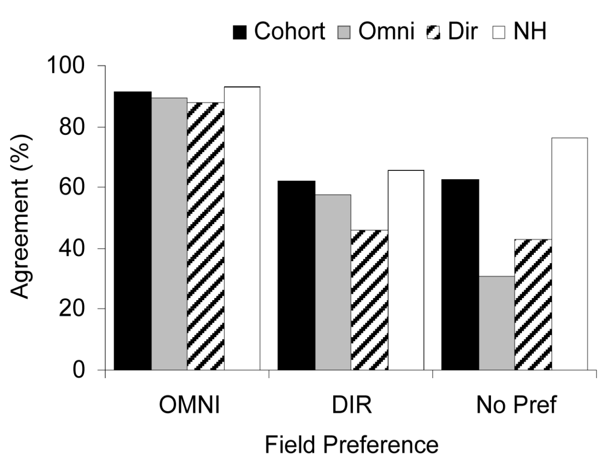

Figure 9. Agreement of laboratory ratings with the field preferences for each participant group.

Given that the Cohort group, on average, had the most hearing loss of the participant groups and the NH group, by definition, had the least, it seems unlikely that hearing loss, per se, explains the group differences observed. However, excluding the NH participants, the average hearing losses of the participant groups did not differ greatly (see Figure 2), thereby limiting the potential influence of this variable. Perhaps the most obvious audiometric difference between the three HI participant groups was that the Cohort group had, on average, flatter audiograms than the Omni and Dir groups. Recall that the field recordings were made with the hearing aid that was programmed based on the mean audiogram of the 17 participants in Walden et al (2004), from which the two field raters and the eight members of the Cohort group were selected. As shown in Figure 1, these individuals had relatively flat audiometric configurations, whereas the average audiograms of Omni and Dir participant groups were more sloping (see Figure 2). It is likely, therefore, that the amplification parameters programmed into the hearing aid (e.g., compression ratios) were less appropriate to the Omni and Dir groups than for the Cohort group. This suggests that audiometric configuration could have contributed to the degree of agreement with the field ratings. That the NH participants had, by definition, flat audiometric configurations and, with the Cohort group, showed more consistent agreement with the field preferences may support this interpretation as well. This possibility was explored further in the following analysis.

Although the slope of the mean audiograms differed slightly among the three HI participant groups, there was considerable overlap among individual participants across the three groups. The possible influence of audiometric configuration, therefore, was further explored by selecting the three participants from each of the HI groups with the best hearing thresholds at 500 Hz (n = 9) and the three participants with poorest thresholds at 500 Hz (n = 9). The two newly formed groups will be referred to as the “Sloping” and “Flat” groups, and their mean audiograms are shown in Figure 10. If the audiometric configuration and/or the appropriateness of the amplification parameters to the participant's hearing loss had a significant effect on the degree of agreement of the laboratory ratings with the field preferences, one would expect that the Sloping group would show less agreement with field preferences than the Flat group. However, this was not observed. The percent agreement of the laboratory ratings with the field preferences for the Sloping and Flat groups is shown in Figure 11. Agreement between field preferences and laboratory ratings for the two groups were not significantly different ($\chi^2 = 1.14$, $p = 0.57$), and, if anything, these findings are in the opposite direction to that hypothesized. Hence, these data provide little support for the notion that audiometric configuration was a significant influence in the level of agreement of the laboratory ratings with the field preferences.

DISCUSSION

This study was motivated by a general interest in the development of effective automatic directionality algorithms in hearing aids. Such an algorithm would automatically switch to the preferred microphone processing mode (omnidirectional or directional) based on an analysis of the acoustic environment. Although beyond the scope of this discussion, there are a number of technical and other problems that complicate the design of algorithms that can consistently make correct decisions regarding the preferred microphone mode in everyday listening. However, one of these potential difficulties is the possibility that HI patients who are audiometrically similar are, nevertheless, quite individual in their preferred microphone mode in everyday listening. To explore this issue, the extent to which microphone preferences based on recordings of everyday listening environments agreed with live microphone preferences in those environments were compared across HI listeners.

Intrasubject Agreement

As noted earlier, the most direct way to explore the robustness of microphone preferences in everyday listening situations would be to have several HI persons make microphone preferences in identical listening situations. However, this is nearly impossible because of the dynamic and individual nature of everyday listening environments. The approach used in this study was to record everyday listening environments through the two microphone modes and have listeners make preference judgments based on the recordings. This assumes that the basis for microphone preferences in everyday listening situations is largely contained in the acoustic input. That the field raters were able to replicate their live microphone preferences in the laboratory with a relatively high degree of accuracy suggests that this assumption is valid, at least to a first approximation.

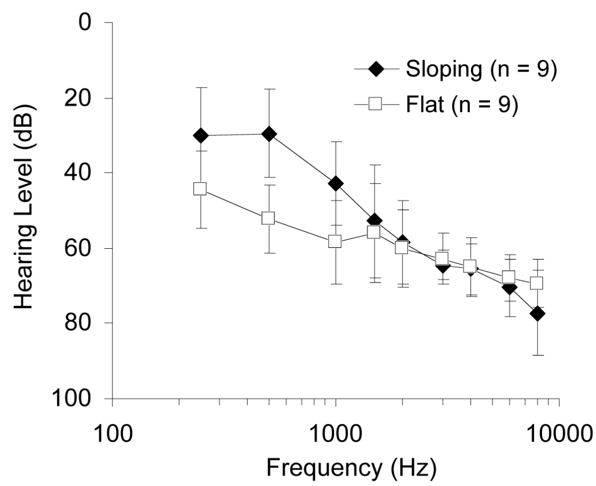

Figure 10. Mean audiogram for the three participants in each HI group with best pure-tone thresholds at 500 Hz (Sloping group) and for the three participants in each group with the poorest thresholds at 500 Hz (Flat group). The bars indicate one standard deviation.

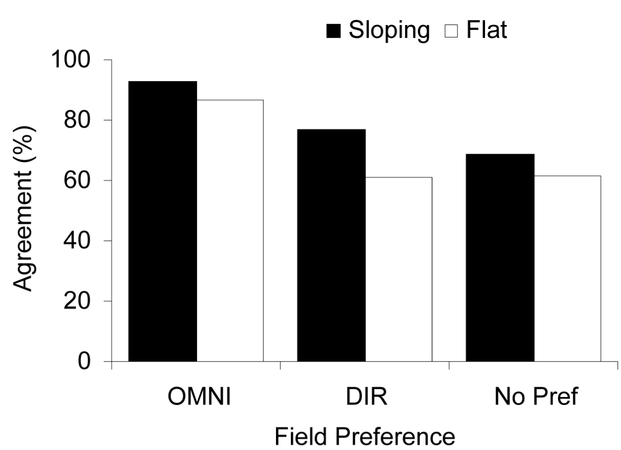

Figure 11. Agreement of laboratory ratings with field preferences for the Sloping and the Flat groups for each preference category.

Clearly, however, this was truer for omnidirectional microphone preferences than for directional preferences. Omnidirectional processing was preferred in the laboratory by the field raters for >95% of the recorded items from the OMNI-preferred sites. About 80% of the directional field preferences were replicated in the laboratory. The implication is that whatever factor(s) make omnidirectional processing preferable in a listening environment are well represented in the acoustic input.

A characteristic common to each of the four OMNI-preferred sites was that the primary signal (talker) was not located in front of the listener. In contrast, the signal was in front for all four DIR-preferred sites. Taken together, this suggests that the relative intelligibility of the primary talker in the two processing modes was the basis for the preference judgments, consistent with the findings of Walden et al (2005). Given that directional processing is designed to improve the SNR of sounds coming from the front by reducing the level of sounds originating from the sides and/or back, it is reasonable to assume that a signal of interest coming from the side or behind the listener may be more intelligible in the omnidirectional mode. However, as important as the location of the signal source appears, this factor alone is not sufficient to create a distinct preference for omnidirectional or directional processing in everyday listening situations. The field raters readily identified everyday listening situations where they had no preference for either microphone mode, consistent with the findings of Surr et al (2002) and Walden et al (2004). In all of these field studies, HI listeners frequently expressed no preference for either omnidirectional or directional processing in everyday listening situations where the signal of interest was coming from the front, as well as from the side or behind the listener. Although talker location may not be the sufficient determinant, nevertheless, it is possible that the relative intelligibility of the talker of interest is the determining factor in microphone preferences in everyday listening. It is not always the case that speech signals located in front of the listener in a noisy listening environment will be more intelligible in the directional mode, due to other environmental factors that compromise the directional processing such as talker-to-listener distance and reverberation in the listening environment (Ricketts and Hornsby, 2003). When directional microphones are unable to improve the SNR noticeably due to such environmental factors, the listener may have no preference for either processing mode.

If it is to be argued that the relative intelligibility of the signal of interest through the two processing modes is the primary determinant in microphone preference, some explanation is required for why omnidirectional field preferences were consistently replicated in the laboratory by the field raters, whereas these participants were less consistent in replicating their directional field preferences when listening to the acoustic recordings. That is to say, if the omnidirectional mode was consistently preferred both in the field and in the laboratory recordings when omnidirectional processing provided the better intelligibility, should this not be true for directional processing as well? For the most part, this was true in that nearly 80% of the field preferences for directional processing were replicated in the laboratory recordings. Still, there was not as much agreement by the field raters between their field and laboratory preferences for the DIR-preferred sites as for OMNI-preferred sites.

Intelligibility may still provide the primary explanation for microphone preferences if we consider the possible influence of visual cues. When the talker (i.e., signal of interest) is not in front of the listener, visual speech cues (speechreading) are not available. Thus, the relevant information concerning the speech signal is restricted to acoustic cues, which are captured by the recordings. In contrast, when the talker is in front, the listener can use visual cues to compliment the auditory input. In this case, intelligibility is affected both by the acoustic signal and by nonacoustic factors not captured in the recordings. It is well known that there is a nonlinear relationship between SNR and the benefit of visual cues to speech recognition (Sumby and Pollack, 1954). Small changes in the SNR that are barely noticeable through audition alone can result in substantial changes in speech intelligibility when combined with visual cues (Grant and Braida, 1991). It is possible that the directional processing provided only a minimal improvement in SNR in some of the DIR-preferred sites included in this study, possibly due to the effects of talker-to-listener distance, reverberation, and/or less than optimal spatial separation of the signal and noise sources. Nevertheless, a small improvement in SNR, when combined with visual speech cues available on the talker's face, may have resulted in a noticeable improvement in overall intelligibility in the field. However, because the recordings from the DIR-preferred sites contain only the auditory information, small changes in SNR may have been minimally noticeable in the laboratory testing, making no preference for either microphone mode more likely. The possible influence of visual cues in patient preference and acceptance of directional microphone processing, as well as on hearing aid benefit in general, is largely unknown and deserves investigation (Walden and Grant, 1993; Walden et al, 2001).

Intersubject Agreement

As already noted, automatic signal processing algorithms such as digital noise reduction and automatic directionality, as they are currently implemented, assume that the same processing mode will be preferred by virtually all HI listeners in a particular listening environment. Once the amplification parameters (e.g., gain, compression, frequency response) have been determined and the hearing aid fit to the patient, the automatic algorithm will sample the acoustic input and apply a decision rule to determine which processing mode will be activated. For the most part, these decision rules are applied independent of listener variables; that is, they are based solely on an analysis of the acoustic input. Consequently, it must be assumed that the preferred signal processing in a particular acoustic environment is relatively constant across HI listeners with roughly comparable hearing losses. The results of this study of microphone preferences suggest that this assumption may be only partially true. Clearly, preferences for omnidirectional processing appear to be highly robust. If a given HI listener strongly prefers omnidirectional processing in a particular noisy listening environment, it is quite likely that other HI listeners will also prefer this processing mode. This is less the case, however, for directional processing. In this study, the field preferences for directional processing were replicated only about 57% of the time in the laboratory across all participants. This is substantially less than the nearly 80% agreement that was observed for the field raters. Hence, it appears that one cannot assume with a high degree of certainty that different listeners will all prefer directional processing in the same listening environment. However, it is notable that, when laboratory ratings did not agree with field preferences for directional processing, listeners almost always expressed no preference for either processing mode. These data suggest, therefore, that it is unlikely that some listeners will strongly prefer omnidirectional processing and others will strongly prefer directional processing in the same listening environment.

If we can interpret no preference to mean that it does not matter to the listener which microphone processing mode is activated, this would appear to minimize the practical implications of the lack of perfect agreement between the field and laboratory ratings. Generally, switchable omnidirectional/directional hearing aids must be in one processing mode or the other. There were very few instances in this study where omnidirectional processing was preferred in a live everyday environment and directional processing was preferred based on the acoustic recording of that environment, or vice versa. If it really does not matter which of the two microphone modes is activated when the listener has no preference for either, the individual differences in microphone preferences observed in this study may not have serious implications for automatic directionality algorithms that are based solely on an analysis of the acoustic input. This possibility could be examined by eliminating the no-preference response category in future studies.

The data of this study do not allow a precise explanation of why preferences for directional processing appear less robust than preferences for omnidirectional processing. Factors such as degree of hearing loss, audiometric configuration, experience with directional microphones, and overall hearing aid use did not seem highly influential in this regard. There was some evidence that the level of agreement between the laboratory ratings and the field directional preferences varied somewhat with the DIR-preferred site (see second panel of Figure 7). It may be that the influence of visual cues already discussed could have contributed to this lack agreement across the participants. Assuming one or more of the live directional preferences of the field raters were influenced by visual cues, this influence would not be captured in the acoustic recordings of those environmental sites. As was the case for the intrasubject data discussed above, this would likely lead to more no-preference ratings in the laboratory for those sites by all participants, despite the unequivocal preference for directional processing by the field rater in the actual listening situation. This explanation requires considerably more study before being accepted. However, its plausibility is perhaps increased by the fact that the two DIR-preferred sites for which the field raters showed the least agreement between their laboratory and live field ratings (conference room, outside building) were also the two sites for which the other 38 participants showed the least agreement.

An additional factor that may have influenced intersubject agreement for DIR preferences is individual differences in directional benefit and the SNR(s) at which this benefit is optimal. Recall that every HI participant had to obtain a DA of at least 15% to be enrolled in the study, and three SNRs were used to achieve this minimum criterion. The actual DA achieved ranged from 15–65% across the 30 HI participants. Walden et al (2005) demonstrated that individual HI listeners can achieve their maximum DA at different SNRs. It is likely that participants derived varying amounts of directional benefit in each of the 12 everyday listening environments (SNRs) included in the study. At the extreme, if a participant failed to derive a directional advantage at a given SNR where other participants benefited significantly from directional processing, that individual would be unlikely to show a strong preference for the directional mode. As a preliminary exploration of this issue, DA was compared with the percentage of DIR preferences across the DIR-preferred sites for the 30 HI participants. No significant relationship ($r = -0.15$, $p = 0.46$) was observed between these two variables, suggesting that the magnitude of the DA obtained in the laboratory was not a factor in the degree of agreement between the laboratory DIR preferences and the field preferences. This is in general agreement with that of Cord et al (2004), who observed that success with directional microphone hearing aids is not predicted by the magnitude of the DA obtained in clinical testing. However, this finding is limited by the use of different SNRs to obtain estimates of DA and the likelihood that SNR varied considerably across the 12 everyday listening environments. A more systematic examination of this issue is required before patient directional benefit, as measured by DA, can be eliminated as a potential factor in the robustness of directional microphone preferences.

Implications for Hearing Aid Design

The results of this study provide only a partial answer to whether or not individual patient differences must be considered in the development of effective automatic signal processing algorithms. It appears that omnidirectional microphone preferences in daily listening are highly robust. Although this appears less true for directional preferences, it is the case that an omnidirectional preference was almost never expressed in the laboratory for a DIR-preferred site recording. It is probably reasonable to conclude that these data do not provide strong evidence that AD algorithms must be customized to reflect individual patient differences, although these data do not rule out this possibility altogether.

Beyond the issue of individual differences in microphone preferences, the results of this study appear to have additional implications for the development of effective AD algorithms, as well as for the potential benefits of directional microphone processing in general. Recall that all of the everyday listening environments in this study included background noise. Consistent with earlier field studies from this laboratory (Surr et al, 2002; Walden et al, 2004), it is clear that there are many noisy listening situations encountered in everyday living in which omnidirectional processing will be preferred by the listener. Hence, a simple AD decision rule that activates directional processing whenever noise is detected in the acoustic input will inevitably lead to errors in selecting the preferred microphone processing mode. Similarly, for manually switchable omnidirectional/directional hearing aids, a strategy in which the patient switches to the directional mode whenever noise is present will also lead to errors. Although the presence of noise (spatially separated from the signal source) is a necessary characteristic for directional benefit, other conditions must also exist in the environment related to the location and distance of the talker relative to the listener and/or the amount of reverberation present. If one adopts a "scene analysis" approach to AD (see Walden et al, 2005, for a discussion of scene analysis versus direct comparison approaches to AD), it is clear that there are multiple characteristics of the listening environment that must be detected in the acoustic input in order for the algorithm to select the preferred microphone mode consistently, the presence of noise being but one. On the other hand, if a "direct comparison" approach is adopted in which the relative fidelity (e.g., SNR) of the two processing modes is compared as the basis for microphone selection, the specific (physical) characteristics of the listening environment need not be determined. However, the data of this study suggest that the relative fidelity of the acoustic input through the two microphone modes may not always definitively determine the preferred microphone mode in everyday listening. Perhaps more precisely, and in contrast to laboratory findings, the magnitude of the intelligibility difference (Walden et al, 2005) and the fidelity difference (Grant et al, forthcoming) through the two processing modes may not be monotonically related to the probability of a preference for one microphone mode or the other due to the possible influence of visual cues and/or possible individual differences in how aggressively a patient wishes directional processing to be applied in everyday listening. Another potential limitation of direct comparison approaches to AD (and of many scene analysis strategies, as well) is that such strategies cannot account for listener intent; that is, which "signal" in the environment is of interest. As long as the hearing aid wearer turns to face the signal of interest, this potential problem will be minimized. However, when the signal of interest is not in front of the listener, which occurs often in everyday listening (Walden et al, 2004), direct comparison approaches to AD will be susceptible to errors in selecting the preferred microphone mode.

Whether one adopts a scene analysis or a direct comparison approach to AD, it is necessary for the hearing aid to sample and analyze the acoustic input at some point in the signal processing. The most convenient point is at the digital signal processor. This is the approach taken by most, if not all, implementations of AD to date. However, sampling the acoustic input at this point does not account for the spectrum shaping and other signal processing that occurs within the receiver, earmold, and ear canal of the hearing aid wearer. Recall that the recordings of the everyday listening environments in this study were made at the output of the digital signal processor, before transduction by the receiver. That the field raters were able to replicate their live microphone preferences from the laboratory recordings with a high degree of accuracy—essentially perfect accuracy for the OMNI-preferred sites—suggests that it is not necessary to consider receiver, earmold, and/or ear canal influences in automatic signal processing algorithms; that is, the input signal can be sampled and analyzed at the digital signal processor stage. Although alterations to the signal will occur as a result of receiver transduction, and earmold and ear canal acoustics, there is little reason to believe that these changes would be large enough to result in a reversal of the preferred processing mode in a particular listening environment.

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Appendix 1. Hearing Aid Use Log for Recording

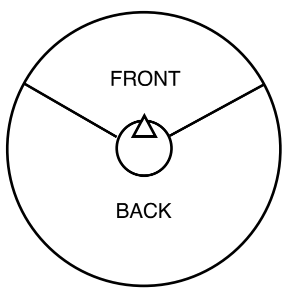
Name:______________________________ Time:_________ Date:_________ Clinician: __________

For this person OMNI is: ___ Program 1 ___ Program 2

1. Describe the listening situation: ____
____
____
____

2. Program preference:
___ Program 1 ___ No Preference ___ Program 2

3. Where was the primary talker/sound located?
___ Front ___ Side ___ Back



4. How far was the primary talker/sound?
___ Less than 3 feet ___ 3–10 feet ___ More than 10 feet

5. Was noticeable background noise present?
___ Yes ___ No

6. If yes, was the noise?
___ Soft ___ Moderate ___ Loud

7. Describe the noise: ____
____
____
____

8. After the recording, program preference:
___ Program 1 ___ No Preference ___ Program 2

9. Reasons for preference: ____
____
____
____