Effect of Signal-to-Noise Ratio on Directional Microphone Benefit and Preference

Brian E. Walden*
Rauna K. Surr*
Kenneth W. Grant*
W. Van Summers*
Mary T. Cord*
Ole Dyrlund†

Abstract
This study examined speech intelligibility and preferences for omnidirectional and directional microphone hearing aid processing across a range of signal-to-noise ratios (SNRs). A primary motivation for the study was to determine whether SNR might be used to represent distance between talker and listener in automatic directionality algorithms based on scene analysis. Participants were current hearing aid users who either had experience with omnidirectional microphone hearing aids only or with manually switchable omnidirectional/directional hearing aids. Using IEEE/Harvard sentences from a front loudspeaker and speech-shaped noise from three loudspeakers located behind and to the sides of the listener, the directional advantage (DA) was obtained at 11 SNRs ranging from -15 dB to +15 dB in 3 dB steps. Preferences for the two microphone modes at each of the 11 SNRs were also obtained using concatenated IEEE sentences presented in the speech-shaped noise. Results revealed that a DA was observed across a broad range of SNRs, although directional processing provided the greatest benefit within a narrower range of SNRs. Mean data suggested that microphone preferences were determined largely by the DA, such that the greater the benefit to speech intelligibility provided by the directional microphones, the more likely the listeners were to prefer that processing mode. However, inspection of the individual data revealed that highly predictive relationships did not exist for most individual participants. Few preferences for omnidirectional processing were observed. Overall, the results did not support the use of SNR to estimate the effects of distance between talker and listener in automatic directionality algorithms.

Key Words: Automatic directionality, directional microphones, hearing aids, preferences, signal-to-noise ratio, speech recognition

Abbreviations: AASC = Army Audiology and Speech Center; DA = directional advantage; DIR = directional; IEEE = Institute of Electrical and Electronic Engineers; OMNI = omnidirectional; SNR = signal-to-noise ratio; WDRC = wide dynamic range compression

Sumario
Este estudio examina la inteligibilidad del lenguaje y las preferencias para el procesamiento en audífonos con microfones direccionales y omnidireccionales, a lo largo de un rango de tasas señal/ruido (SNR). Una
Although laboratory studies have consistently shown superior speech understanding in background noise for hearing aids with directional microphones compared to instruments with an omnidirectional microphone (Valente et al., 1995; Ricketts and Dahr, 1999), less consistent benefit has been obtained in field trials (Nielsen and Ludvigsen, 1978; Valente et al., 1995; Walden et al., 2000). Studies by Cord et al. (2002) and Surr et al. (2002) suggested that the performance of directional microphones in everyday listening is highly dependent on the characteristics of the listening environment. Specifically, the location of the primary talker, presence or absence of background noise, and type of space in which the communication occurred significantly influenced patient preferences for directional microphones over an omnidirectional microphone.

Walden et al. (2004) conducted a field trial to determine whether patient preferences for omnidirectional processing or directional processing in everyday living might be predicted from the characteristics of the listening environment. Microphone preferences were obtained from 17 hearing-impaired adults in 1599 everyday listening situations. The omnidirectional mode tended to be preferred in relatively quiet listening situations or in the presence of background noise when the signal source was not located in front of the listener and/or 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 to the listener.

One of the limitations of traditional switchable omnidirectional/directional hearing aids is that the user must manually set the microphone mode, depending on the listening situation. This appears to be a problem for many patients. Cord et al. (2002) observed that nearly one-third of persons wearing manually switchable
omnidirectional/directional hearing aids did not switch between the two microphone settings; that is, they left their instruments permanently set in the default omnidirectional mode, regardless of the listening environment. The initial efforts of these patients to use the directional mode may have resulted in little or inconsistent benefit, possibly because they did not reliably select the optimal processing mode when difficult listening environments were encountered.

To address the limitations of manual switching, hearing aid manufacturers have developed algorithms that automatically switch between microphone modes. Automatic directionality involves an analysis of the acoustic environment to determine whether omnidirectional or directional processing is preferable. Early attempts focused on a determination of whether noise was present in the environment based on overall input level. Acoustic environments with input levels that exceeded a specific criterion were assumed to include background noise, and therefore, the directional mode was activated. Given that directional microphones are designed to improve speech understanding in background noise, the logic of this simple strategy is obvious. Early implementations of automatic directionality, however, did not achieve widespread acceptance clinically, presumably because they frequently failed to select the optimal processing mode for the patient. Recall that participants in the Walden et al (2004) study reported a significant preference for omnidirectional processing in some noisy listening environments, especially when the signal source was not in front of the listener and/or was at a distance. Consistent with this finding, Walden et al also observed that, on average, patients reported being in listening environments where background noise was present approximately two-thirds of their active listening time, but they expressed a preference for directional processing only about one-third of the time. Similarly, the data of Ricketts et al (2003) suggested that a directional disadvantage can be expected in some everyday noisy listening situations.

Currently, manufacturers are developing—and, in some cases, introducing commercially—more sophisticated strategies for automatic switching. These generally involve one of two fundamental approaches. The first involves acoustic analyses to determine the characteristics of the listening environment (i.e., auditory scene analysis). The goal is to identify specific characteristics of the listening environment that are known to influence microphone preferences, such as the locations of the signal and noise source(s), reverberation conditions, and so forth. When the acoustic analysis predicts that the listening environment is more conducive to omnidirectional or directional processing, the hearing aid automatically switches to the preferred microphone mode. The second fundamental approach to automatic switching involves a comparison of the acoustic environment processed through each microphone mode (i.e., direct comparison). This is done in the background; that is, within the processor but not audible to the hearing aid wearer. The microphone processing mode that provides the better fidelity (defined in various ways) in a given acoustic environment is then activated.

Both approaches to automatic directionality involve a number of technical problems that are currently being addressed by manufacturers and hearing scientists. This paper focuses on issues related to the first approach, that is, identifying characteristics of the listening environment that are known to favor one microphone mode or the other.

Regardless of which of these two fundamental approaches to automatic directionality is utilized, the goal is the same: to set the hearing aid in the microphone mode that is preferred by the hearing aid wearer as the listening environment changes. Although a preference for directional processing in certain (appropriately configured) noisy listening situations is not surprising, given the nature of the signal processing provided, it is not immediately evident why an omnidirectional microphone is distinctly preferred to directional microphones in many everyday listening situations (Walden et al, 2004). For example, in a relatively quiet listening environment, one might assume that there should be little difference between a speech signal processed through the omnidirectional and directional modes, assuming that the source of that signal is in front of the listener. However, as noted earlier, there is an overwhelming preference for omnidirectional processing in relatively quiet listening environments.
In surveys conducted by Cord et al (2002) and Walden et al (2004), patients fit with manually switchable omnidirectional/directional hearing aids reported using their instruments set in the omnidirectional mode, on average, at least two-thirds of the time. Further, the data of Walden et al (2004) suggest that patients will generally use the omnidirectional mode in listening environments in which there is not a clearly perceptible performance advantage for directional processing. This does not appear attributable to the omnidirectional mode typically being the default microphone setting (Walden et al, 2004). It appears, rather, that there is something about omnidirectional processing and/or something about directional processing that seems to favor the omnidirectional mode in everyday use when a clear performance advantage for the directional mode does not exist. This observation is consistent with Ricketts et al (2003), who reported that factors other than speech recognition may influence patients' perception of directional benefit in everyday living. This generally accepted (although not well defined) notion undoubtedly is the basis for manufacturers recommending and audiologists using omnidirectional processing as the default microphone mode.

One reasonable explanation for the general preference for omnidirectional processing is that it more closely approximates normal hearing. That is to say, it is equally sensitive to sounds emanating from all directions. Obviously, this is advantageous when the signal of interest is not in front of the listener. However, it also provides for better localization of sound (Ricketts et al, 2003) and may also provide a greater and more natural sense of connection with the acoustic environment. As such, listener intent becomes an issue. A listener may not always intend to focus on a sound source located in front. Rather, she or he may wish, for example, to overhear a conversation going on behind or to monitor nonspeech sounds coming from various directions that might otherwise be regarded as background noise. Instances where the listener's intent is other than focusing on a speech message coming from the front, while ignoring noise sources coming from other locations in the listening environment, represent a significant challenge to effective automatic switching algorithms.

Because there is a relatively consistent preference for the omnidirectional mode in quiet listening environments (Walden et al, 2004), the challenge in designing automatic switching algorithms is selecting the optimal microphone setting in noisy listening environments; specifically, determining when to remain in the omnidirectional mode. Walden et al suggested that the preferred microphone mode can be determined in the vast majority of everyday listening situations by using the following strategy: Select the directional mode only when (a) background noise is present, and (b) the signal of interest is in front of the listener, and (c) the signal of interest is relatively close (i.e., within approximately ten feet) to the listener. In all other environments, select the omnidirectional mode. This strategy is easily implemented by most patients wearing manually switchable omnidirectional/directional hearing aids. It remains, as noted earlier, that some patients will not manually switch microphone modes for various reasons (e.g., inconsistent benefit, poor dexterity, forgetfulness, inconvenience). For these patients, a switching algorithm that automatically selects the preferred microphone mode would be particularly useful.

The study reported here explores how patient preferences for omnidirectional versus directional processing may vary with the SNR (signal-to-noise ratio) in the listening environment. A primary motivation was to determine whether SNR might be used to represent the effect of distance between the signal source and the listener. Recall that Walden et al (2004) found directional processing to be generally preferred only when noise was present, the signal source was located in front of the listener, and the distance between the signal source and listener was less than ten feet. Given current signal processing technology, an automatic switching algorithm might determine with reasonable accuracy whether noise is present in the listening environment and where the signal source is located, especially if the signal is speech and the noise is spectrally distinct from speech. However, the distance between the signal source and the listener must be derived indirectly. Obviously, the distance between the signal source and
listener, per se, does not influence microphone performance. Rather, it is the consequences of distance on the acoustic environment. For example, signal intensity will generally decrease and reverberation will generally increase with distance (Ricketts and Hornsby, 2003). A third consequence is that, under most circumstances, the SNR may vary systematically. Assuming the most typical listening situation where the signal source (e.g., talker) is in front of the listener and some spatial separation exists between the talker and noise source(s) in the listening environment (Walden et al, 2004), the signal will get less intense and the noise typically more intense as the distance between the talker and listener increases. Hence, the SNR will get progressively worse.

Following this reasoning, this study explored whether SNR might be used to reflect the influence of distance on microphone preferences observed by Walden et al (2004). Specifically, we sought to determine if there is an optimal range of SNRs within which directional processing is preferred.

**METHOD**

**Participants**

Thirty-one experienced hearing aid users participated in the study. Their mean age was 71.7 years (SD = 6.5, range = 58–81), and they had used amplification for an average of 8.4 years (SD = 6.8, range = 0.5–28). All but one were male, reflecting the demographics of the Army Audiology and Speech Center’s (AASC) patient population. At the time of enrollment, all participants wore binaural hearing aids a minimum of three hours per day (M = 12.0 hours, SD = 4.5, range = 3–18). Their current hearing aids had been fitted at the AASC at least three months and not more than 72 months prior to enrollment in the study. Two groups of participants were recruited based on the type of hearing aids they were wearing. Sixteen wore hearing aids equipped with only omnidirectional microphones, whereas the remaining 15 participants used instruments with a manually switchable omnidirectional/directional microphone option (hereafter, referred to as the “Omni-Only” and “Omni-Dir” groups, respectively). For inclusion in the latter group, potential participants had to report regular, though not necessarily equal, use of both microphone modes. Specifically, the study required that these patients report using each microphone setting at least 10% of the time in daily listening.

All 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. Monosyllabic word recognition (NU-6) in quiet was 50% or better in each ear at a comfortable listening level.

The mean audiogram of the participants in each group is shown in Figure 1. On average, the participants in both groups had moderate-to-severe, gradually sloping, bilaterally symmetric, sensorineural hearing loss. Statistical comparisons of audiometric indices obtained from each group suggested that, on average, they were well matched for these measures. Audiometric thresholds for the two participant groups, averaged for the left and right ears, were compared using a two-way ANOVA (analysis of variance). The results showed a nonsignificant group effect (F = 1.94; p = 0.16) and, as expected, a
significant frequency effect ($F = 73.94; p < 0.001$). However, the group X frequency interaction was not significant ($F = 0.34; p = 0.95$). The two participant groups were also compared for speech recognition scores, as well as for demographic measures. Mean NU-6 word recognition (averaged across right and left ears) in quiet under earphones at a comfortable listening level was 83.1% (SD = 12.5, range = 60–100) for the Omni-Only group and 81.5% (SD = 15.1, range = 50–100) for the Omni-Dir group. These mean scores were not significantly different ($t = 0.47; p = 0.64$). Similar statistical comparisons of mean age, number of years of hearing aid use, and hours of reported daily hearing aid use did not reveal significant differences between the two groups.

**Hearing Aids and Fitting Procedures**

Upon enrollment in the study, all participants were fitted bilaterally with GN ReSound Canta770D behind-the-ear instruments using the Audiogram + fitting algorithm of the Aventa 1.2 software. The Canta7 series is a multiband, multimemory digital hearing aid with variable wide dynamic range compression (WDRC). Directionality is achieved electronically via a two-microphone system and includes an adaptive polar pattern option that was used throughout this study. However, in diffuse background noise (see below), the Canta7 defaults to a hypercardioid polar response. 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 randomly programmed into one of the two memories, and the directional mode was programmed into the other (hereafter, referred to as the “OMNI” and “DIR” programs, respectively). A push button on the back of the instrument allows the wearer to switch between programs. An appropriate number of audible tones inform the user whether program 1 or program 2 has been activated.

The frequency responses of the OMNI and the DIR programs were equalized (using the Max Bass Boost option in the fitting software) to minimize the effect of the low-frequency roll-off typically associated with directional microphones. Digital feedback suppression was not needed for any of the participants, and the digital noise reduction feature was not used.

The hearing aids were fitted to participants in a quiet test booth in accordance with standard clinical practice. Custom lucite earmolds with a select-a-vent option were used in all fittings. The medium size vent was chosen for the majority of the fittings, and no open earmold fittings were utilized. For the purpose of possible programming fine-tuning, each individual was asked several open-ended questions during informal conversation regarding the quality and comfort of listening to the audiologist’s voice and to the wearer’s own voice. All responses were positive to the initial programming, and, therefore, no adjustments were made to the prescribed fittings for any of the participants. Participants were not informed of the specific nature of the signal processing provided by the two programs; that is, they were not told that the two programs represented omnidirectional- and directional-microphone processing. Rather, they were simply informed that the two programs were different ways of processing sound.

The mean frequency responses, 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 2. These 2-cc coupler measurements (Fonix 6500-CX) were made in the OMNI mode and show the

[Figure 2. Mean omnidirectional 2-cc coupler gain of the test instrument averaged for the right and left ear fittings for three input levels (50, 65, 80 dB SPL), as well as the directional mode with a 65 dB SPL input signal.]
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 (also displayed in Figure 2 as one of the two middle and overlapping curves) to assure that the frequency-gain characteristics of the OMNI and DIR programs were similar (equalized). Differences between the mean frequency responses of the two programs were minor, as were differences across individual fittings.

**Speech Recognition in Noise**

Sentence recognition in noise was assessed for each microphone mode at 11 SNRs ranging from -15 dB to +15 dB in 3 dB steps, using recordings of the IEEE (Institute of Electrical and Electronic Engineers)/Harvard sentences spoken by a female talker of American English (Institute of Electrical and Electronic Engineers, 1969). The IEEE sentences were used because there are sufficient equivalent lists for the number of test conditions included in this study. These materials consist of 720 sentences, organized into 72 phonetically balanced ten-sentence lists. Each sentence contains five key words that form the basis for scoring (percent correct). The sentences contain few contextual cues to help identify the key words (e.g., “The birch canoe slid on the smooth planks.”). The standard deviation for repeated tests with three ten-sentence lists (i.e., 150 keywords) is 5–10% across a broad range of SNRs (Grant and Braida, 1991).

Each of the 22 speech recognition scores obtained from each participant (2 microphone modes X 11 SNRs) was based on responses to three lists, which were randomly dispersed throughout the testing. Hence, participants listened to only ten sentences at a time for a given test condition to reduce listener frustration at the most unfavorable SNRs where the sentences were nearly or completely unintelligible.

The sentence lists were presented at an average conversational level of 65 dBA through a loudspeaker located 1.2 meters in front of (0° azimuth) the listener. The competing noise was speech-shaped white noise having a spectrum equal to the long-term spectrum of the IEEE sentences. The noise was turned on preceding each IEEE sentence, using a 1 sec cosine on-ramp. Similarly, 250 msec cosine off-ramp turned the noise off following each sentence. The level of the noise was varied to achieve each SNR. Although it could be argued that varying the level of the sentences may have been more analogous to variations in distance between talker and listener, the speech signal presentation level was held constant to ensure equal audibility of the sentences across the test conditions, apart from the masking effect of the noise. By doing so, the influence of SNR could be assessed as a distance measure without the confounding influence of a priori differences in audibility. Following the same reasoning, reverberation was constant across the test conditions, although it would be expected to vary with listening distance in realistic listening environments.

For each SNR tested, the background noise was presented uncorrelated through three loudspeakers positioned to the sides and behind the listener (90°, 180°, and 270° azimuths). The rear loudspeaker was located 1.5 meters and two side loudspeakers 1.2 meters from the center of the participant’s head. These loudspeakers were calibrated such that each loudspeaker presented the same level, measured in an empty room at the location normally occupied by the listener’s head, at any given attenuator setting of the noise. The noise level required to create each SNR condition was based on the overall level of the three noise sources measured at the location normally occupied by the listener’s head. Calibration was checked daily.

Presentation of the test sentences was under computer control. Software randomly selected the order of presentation of 66 lists (22 test conditions X 3 lists/condition) for each participant, and attenuator settings for each condition were automated. Each sentence appeared on the tester’s computer screen with the key words highlighted. Participants responded verbally to each test sentence, and the test administrator entered online the number of correct responses to each sentence. The score for each test condition was derived automatically. Two one-hour test sessions per participant were needed to complete the speech recognition testing.

**Preference Ratings**

In a separate test session following the speech recognition testing, preference
judgments between the two microphone modes were obtained at the 11 SNRs. The sentences of randomly selected IEEE lists were concatenated to produce continuous speech. The concatenated sentences were presented at 65 dBA from the front loudspeaker and, as in the speech recognition testing, speech-shaped noise was varied in level from the other three loudspeakers to create the 11 SNR conditions. At each SNR, participants were asked to switch several times between programs 1 and 2 (OMNI and DIR modes) and to rate their preference using a three-category scale (Prefer Program #1; No Preference; Prefer Program #2). The response options were displayed on the wall of the test booth in front of the participant while this testing was administered. Initially, 40 seconds of concatenated sentences were presented, allowing several switches between the two programs. Most participants found this to be ample time to arrive at a preference rating, although the duration could be varied depending on the participant's needs. Each of the 11 SNRs was presented five times for preference rating, randomly dispersed throughout the testing. The preference data collection took approximately 45 minutes.

RESULTS

Speech Recognition in Noise

IEEE scores were transformed into rationalized arcsine units (rau; Studebaker, 1985), which closely approximate percent correct scores from 15–85%. A two-way ANOVA was performed to compare the two participant groups (Omni-Only and Omni-Dir hearing aid users) and the two microphone modes (OMNI and DIR) across the 11 SNR conditions. The results revealed no significant group effect (F = 0.01, p = 0.95) but a highly significant microphone effect (F = 18.87, p < 0.001). Further, no statistically significant interaction between group and microphone mode (F = 0.003, p = 0.95) was observed. Consequently, data for the two participant groups were combined for all subsequent analyses.

Mean speech recognition for each microphone mode and SNR is shown in Figure 3. At the most unfavorable SNR (-15 dB), listeners were unable to identify any of the words in the OMNI mode, and only one individual was able to identify two words in the DIR mode. However, speech recognition improved under both processing modes as the SNR improved, reaching asymptote at the most favorable SNRs where mean performance on the IEEE sentences approximated the participants' mean unaided speech recognition (NU-6) scores in quiet.

Speech recognition was higher for the DIR mode than for the OMNI mode, except at the most unfavorable and the most favorable SNRs. Repeated-measures ANOVA revealed significant main effects for SNR (F = 771.0, p < 0.001) and for microphone mode (F = 372.4, p < 0.001). In addition, there was a significant interaction between microphone mode and SNR (F = 47.6, p < 0.001). The all pair-wise multiple comparison procedure (Holm-Sidak method [Holm, 1979]; SigmaStat 3.0) was performed with an adjusted overall significance level of 0.05. Results indicated that the differences between the OMNI and DIR modes were statistically significant for all but the -15, -12, and +15 SNR conditions.
In Figure 4, the data of Figure 3 are plotted as the mean directional advantage (DA = DIR score - OMNI score) across the 31 participants. The mean DA ranged from 0.26 rau at -15 dB SNR to 34.3 rau at -3 dB SNR. As the SNR improved beyond -3 dB, the DA steadily decreased.

Despite the systematic variation in the mean DA across SNRs, there was substantial individual variability, as illustrated in Figures 5 and 6. Figure 5 shows the minimum and maximum DA at each SNR for the 31 participants. Every participant obtained a DA of at least 19 rau at one of the SNRs, and at least one participant obtained a DA greater than 15 rau at every SNR but -15 dB. However, at every SNR, at least one participant (but not the same participant) failed to obtain any directional advantage. The considerable individual variability in DA is further illustrated in Figure 6, which shows the maximum DA achieved by each of the 31 participants plotted as a function of SNR. Not only did the maximum DA achieved vary considerably across the participants, but the SNR at which the maximum DA was observed also varied across a range of four SNRs, from -6 dB to +3 dB. Nevertheless, 24 of the 31 participants (77.4%) obtained their maximum DA at either -3 dB or 0 dB SNR, and all but one participant obtained a DA of at least 15 rau at 0 dB SNR.

Microphone Preferences

Recall that each participant made five independent preference judgments between the two microphone modes at each SNR, resulting in 155 preference ratings at each SNR and a total of 1705 ratings across the 11 SNRs. For statistical purposes, numerical values of 1–3 were assigned to OMNI
preferences, no preferences, and DIR preferences, respectively. The median of the five ratings at each SNR was computed for each participant. The means of these median ratings for the two participant groups (Omni-Only, Omni-Dir users) were compared via a two-sample rank sum test. The results revealed no significant group effect ($z = 0.108, p = 0.91$). Consequently, the data for the two groups were combined for all subsequent analyses.

Overall, the DIR mode was preferred 57.7% of the time, and the OMNI mode only 4.5%. The remaining 37.8% of the ratings were no preference. The percentages of OMNI, no preference, and DIR ratings at each SNR are shown in Figure 7. Clearly, there were few preferences for OMNI processing, regardless of SNR. Participants generally either preferred the DIR processing or had no preference for either microphone mode. However, the distribution of DIR preferences and no preferences were not random across SNRs. Preference for DIR processing increased systematically as the SNR improved from the most unfavorable SNRs, where “no preference” ratings were most common, through the midrange of SNRs where there was a rather consistent preference for DIR processing. At the more favorable SNRs, preferences were approximately equally divided between DIR processing and no preference.

The mean of the median microphone preference ratings across the 11 SNRs are shown in Figure 8. Recall that the no preference rating was given a numerical value of two, shown by the horizontal line. It is clear that there was at least a slight mean preference
for DIR processing at every SNR, although preference for DIR processing was strongest for SNRs from -6 dB to +3 dB. A Kruskal-Wallis one-way nonparametric ANOVA was carried out on the preference scores with SNR as the independent variable. The results revealed that SNR had a highly significant effect on the ratings ($F = 8.2, p < 0.001$).

It is noteworthy that the overall shape of the preference data displayed in Figure 8 is similar to that of the speech recognition data displayed in Figure 4, suggesting a relationship between the directional advantage and microphone preferences. To examine this relationship, each data set was converted into z-scores. The mean DA and mean microphone preferences, expressed as z-scores, for each of the 11 SNRs is shown in Figure 9. It is clear that quite a close relationship existed between the mean DA and microphone preferences, suggesting that microphone preferences were determined largely by the relative intelligibility of speech through each microphone mode. Although this is an accurate characterization of the group data, inspection of the individual data revealed less systematic relationships between the directional advantage and microphone preferences across SNRs for many participants. The implications of such individual variability on the design and fitting of omnidirectional/directional hearing aids are discussed below.
DISCUSSION

Experience with Directional Microphones

It appears that experience with directional microphone processing has little influence either on directional advantage or microphone preferences, at least in a laboratory test environment. Mean speech recognition for the two processing modes was not significantly different across SNR for participants who had experience only with omnidirectional hearing aids (Omni-Only group) and those who were experienced with switchable omnidirectional/directional instruments (Omni-Dir group). Similarly, preferences for the omnidirectional and directional processing modes did not differ between the two participant groups across SNR.

It should be noted that participants were not informed of the nature of the signal processing provided by programs 1 and 2, other than that they were different ways of processing sound. Hence, participants did not explicitly know that they were listening through omnidirectional versus directional microphones. Because the participants who were experienced with directional technology were blinded with regard to the signal processing provided by each hearing aid program, any prejudices toward one microphone mode or the other that may have existed for these participants should have had minimal influence on the dependent measures. In any case, for these laboratory measures, experience with directional technology seemed irrelevant. It is unknown whether these findings extend to performance in everyday listening situations, although the data of Ricketts et al (2003) suggest no measurable short-term (two-week trial) acclimatization of directional benefit. To the extent that these findings may be generalized broadly, it appears that the benefit of and preferences for directional processing in novice users of this technology are generally representative of that of more experienced users.

Speech Recognition in Noise

Clearly, a significant directional advantage can be obtained over a relatively broad range of SNRs—in this study, from approximately -9 dB to +6 dB SNR. Outside this midrange of SNRs, the directional advantage tended to diminish. The tendency for the directional advantage to get smaller with improving SNRs was also observed by Valente et al (1999), who examined speech recognition for omnidirectional and directional hearing aids at three SNRs. This does not mean, however, that directional processing only operates within a limited range of SNRs. The DA will disappear at highly unfavorable SNRs because the improved signal processing provided by directional microphones under these very poor listening conditions does not result in a measurable improvement in speech understanding. Similarly, at more favorable SNRs, there may be little difference in performance between the two processing modes because the speech recognition scores are limited by the patient’s inherent speech recognition ability. Even with a substantial improvement in SNR, many patients cannot achieve 100% recognition of speech due to other forms of suprathreshold distortion (e.g., frequency, temporal) that are introduced by hearing impairment. From a clinical perspective, it is important to note that the benefit provided by directional microphones in everyday listening can be limited by the amount of noise present, as well as the patient’s hearing impairment (HG Mueller, pers. comm., cited in Walden et al, 2000, p. 558). Hence, if advantages of omnidirectional processing to the patient not directly related to speech understanding exist (e.g., localization, more natural connection to listening environment), it would appear prudent to activate the directional mode only within the range of SNRs where an actual improvement in intelligibility can be expected.

If the DA is used to verify clinically that a particular patient can benefit from directional processing and/or that the directional microphones are working properly, the data of this study suggest that an SNR of 0 dB or -3 dB should be selected, assuming performance is evaluated at only one SNR. However, this conclusion is based on the specific test materials and procedures of this study. It is likely that a different conclusion would be reached with different speech materials, background noise, and loudspeaker configuration (Ricketts, 2000, 2001). Further, it appears that there is substantial variability.
Among patients regarding the amount of directional benefit obtained and the range of SNRs at which significant benefit is achieved. Not only does this complicate the use of DA as a clinical measure of directional microphone performance, it potentially can add another level of complexity to the development of effective automatic microphone switching algorithms. Notably, at least one participant at every SNR did not obtain any improvement from directional processing. The potential influence of this individual variability on everyday performance of directional microphones is suggested in Figure 10. Shown is the directional advantage at each of the 11 SNRs for two of the participants. Participant 16 achieved the largest DA at -3 dB SNR, whereas Participant 26 obtained maximum benefit at +3 dB SNR. Further, the DA obtained by these two participants differed considerably at many of the SNRs. For example, at +6 dB SNR, Participant 26 achieved nearly his maximum DA, whereas Participant 16 obtained his minimum DA at that same SNR. This suggests that directional processing might not be appropriate for both of these patients in the same listening environment, especially if factors other than speech understanding influence microphone preferences in everyday listening situations when the DA is minimal. In any case, it seems reasonable to assume that these two patients could experience substantially different degrees of benefit from the directional microphones in many everyday listening situations.

Given the individual variability observed in this study, measuring DA at only one SNR in the test booth may not be sufficient to determine the potential benefit of directional microphones to a patient. Similarly, these data suggest that caution must be used when comparing the amount of directionality provided by different hearing aids based upon behavioral data obtained at a single SNR and/or from different subject samples. Although the average maximum DA was 41.3 rau, the 31 participants obtained their maximum benefit from directional processing at four different SNRs (see Figure 6). Hence, depending upon the subject sample and the SNR selected, quite different impressions of the directionality provided by a given hearing aid can be derived from this behavioral measure. In a more general sense, the individual variability observed in the speech recognition data across SNRs suggests that it may ultimately be necessary to program special signal processing circuits such as directionality, noise reduction, and so forth, to the requirements and preferences of individual patients. These might be based on learning algorithms that are incorporated into “intelligent” hearing aids that use input from the patient, acquired during normal use in the patient’s own everyday listening environments.

**Microphone Preferences**

Perhaps the most striking finding of this study was that the OMNI mode was rarely preferred at any SNR. Participants either

![Figure 10. DA at each of the 11 SNRs for two individual participants.](image)
preferred the directional processing or expressed no preference for either microphone mode. It should not be surprising that the DIR mode was usually preferred in the midrange of SNRs where DA was greatest. However, it is perhaps unexpected that, for very unfavorable and very favorable SNRs where the directional processing provided little improvement in speech understanding, few preferences for the OMNI mode were observed. Rather, participants either preferred the directional microphones, despite little or no DA, or had no preference.

At first glance, this finding seems to contradict earlier studies that show a preference for omnidirectional processing under a variety of listening conditions (Cord et al, 2002; Surr et al, 2002; Walden et al, 2004), as well as the clinical convention to program the omnidirectional mode as the default setting in switchable omnidirectional/directional hearing aids. It also does not support the suggestion made earlier that there may be factors that can produce a preference for omnidirectional microphones, even when a directional advantage is obtained in the directional mode. However, at least in a general sense, these laboratory findings are consistent with the findings of Walden et al (2004) that the directional mode will be preferred when noise is present and the signal of interest is in front of and relatively near to the listener. Clearly, noise was present and the signal of interest (IEEE sentences) was in front of and relatively near (1.2 meters) to the listener under every SNR condition. Given that the signal of interest was always presented at 65 dBA, it was comparable to listening to a talker speaking at a normal level in relatively close proximity. So, in this sense, every SNR condition met the criteria of Walden et al (2004) for favoring directional processing. From this perspective, a strategy of switching to the DIR mode when the signal of interest is in front and relatively near appears robust across a broad range of noisy listening conditions. However, it remains that nearly 40% of all the microphone preference ratings were no preference. These were concentrated at the extreme ends of the range of SNRs evaluated, where little or no DA was observed. Notably, when participants did not perceive a clear preference for the directional processing, they did not then prefer the omnidirectional mode. Hence, if there are generalized factors that may cause a preference for omnidirectional microphones in some noisy everyday listening situations, they were not captured by the listening tasks of this experiment that utilized a typical multi-loudspeaker laboratory test arrangement.

CONCLUSIONS

Successful use of directional hearing aids or lack of experience with them does not appear to affect performance with or preferences for directional processing, at least in a laboratory setting. Further, in a laboratory test environment that is structured to favor directional processing (noise present, signal front and near), a directional advantage will be observed across a broad range of SNRs. However, the DA will be limited at quite favorable SNRs due to the inherent limitations of the patient's impaired speech recognition ability, and at highly unfavorable SNRs because speech signals processed through directional microphones remains largely unintelligible. Importantly, both the maximum DA and the SNR at which that maximum advantage is observed vary considerably across hearing-impaired patients. Hence, care must be exercised in generalizing mean performance on these measures for a group of listeners to individual patients.

Preferences for directional processing are closely related to the magnitude of the directional advantage, at least for group data. Hence, to the extent that speech intelligibility is superior in the directional mode compared to the omnidirectional mode, the likelihood that the directional processing will be preferred will increase. Based on these mean laboratory data alone, one might assume that the greater the DA obtained by a patient in the audiometric test suite, the more likely they are to benefit from a directional microphone option in everyday living. However, Cord et al (2004) observed that a large DA obtained in the test booth does not guarantee success with directional microphones in more realistic listening situations. They observed that patient success with directional microphones in everyday listening—defined as whether the patient regularly uses the directional mode or not—could not be accurately predicted from the magnitude of the DA. It should be
noted in this regard that Cord et al assessed the DA at a fixed performance level (i.e., 50% correct recognition) across listeners where the DA should have been optimized, rather than at a fixed SNR where the DA might be more likely to vary across listeners (see above). In any case, it seems reasonable to assume that the more directivity provided by a particular hearing aid, the greater the potential for the patient to benefit from this technology. However, it is apparent that there are many factors that determine success with directional microphones in everyday living. Obtaining a significant DA may be a prerequisite for success but does not guarantee it.

Overall, the results of this study provide little insight regarding why omnidirectional microphones appear to be preferred in some everyday listening situations where background noise is present, as was observed in Walden et al (2004). Further, specific to the primary motivation for this study, these data provide little support for using SNR in automatic switching algorithms to estimate the influence of distance, because omnidirectional processing was not consistently preferred to directional processing at any SNR. In this regard, these results provide additional caution against generalizing the findings of directional microphones in a controlled laboratory test environment to their performance in everyday listening situations (Walden et al, 2000).

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