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Directional hearing aids: Then and now

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Abstract—Directional microphone hearing aids can lead to improved speech recognition when speech and noise are coming from different directions. This technology provides limited benefits, however, and in specific instances use of a directional hearing aid mode can be detrimental. This article discusses the benefits and limitations of directional amplification, summarizes some current work in directional amplification, and recommends clinical application relative to the use of directional amplification.

Key words: critical distance, directional hearing aids, directivity, front-to-back ratio, listening environment, localization, noise reduction, speaker-to-listener distance, speech transmission index.

INTRODUCTION

Recently, directional hearing aids and their ability to improve speech intelligibility have received a great deal of excitement. Directional microphone hearing aids can lead to improved speech recognition when speech and noise arrive from different directions. This technology provides limited benefits, however, and in specific instances, use of a directional hearing aid mode can be detrimental. This article discusses the benefits and limitations of directional amplification. In addition, it summarizes some current work in directional amplification and recommends clinical application on the use of directional amplification. Directional microphones were developed in the 1920s and 30s for use at sporting events and for sound recording. Directional hearing aids were first introduced to the U.S. market in 1971, and a directional in-the-ear instrument was first described by Rumoshovsky in 1977 [1]. In 1980, directional hearing aids represented almost 20 percent of the total hearing aids sold; however, their use steadily declined during the 1980s because (1) directional microphones were generally larger while the trend was moving toward smaller custom instruments, (2) only a few instruments were capable of both omnidirectional and directional modes, and (3) directional microphones were not generally designed specifically for placement in a hearing aid shell placed on the head. The final factor greatly limited directivity [2]. In general, directional hearing aids are designed to provide attenuation to sounds arriving from angles other than in front of the listener. How well they achieve this goal can be quantified electroacoustically by the directivity index (DI). Simply stated, directivity (or, more precisely, the DI) refers

Abbreviations: BTE = behind the ear, CD = critical distance, DI = directivity index, FBR = front-to-back ratio, FM = frequency modulation, HINT = Hearing in Noise Test, HL = hearing level, ILD = interaural level difference, REAR = real ear aided response, REIG = real ear insertion gain, RT60 = time a signal takes to decay to 60 dB, SNR = signal-to-noise ratio, STI = Speech Transmission Index.

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to the average amount of attenuation provided for all possible angles and elevations of arrival relative to the output for sound arriving from directly in front of the hearing aid or listener (0° angle and elevation).

Devices that sample sound at only two locations are commonly called first-order directional microphones while devices that sample at more than two locations are called second-, or higher-, order directional designs (including microphone arrays). For first-order directional microphones, directional processing can be achieved with a single directional microphone and an acoustical phase-shifting network (pressure gradient approach) or the combination of the output of two separate omnidirectional microphones (dual or twin microphone approach). For both methods, sound reduction is based on timing differences between sounds sampled at the two points in space (the two microphone openings of the omnidirectional microphones or two microphone ports of the directional microphone). Depending on the angle of arrival relative to the hearing aid, the sound may arrive at the two microphone ports at different instants. For example, a sound arriving from directly behind the rear microphone port will have a travel time before it reaches the front microphone port. This travel time, often referred to as "external delay," will depend linearly on the distance between the microphone ports, with greater separation resulting in greater travel time. The sound arriving at the rear port can then be delayed (internal delay) by mechanical, electronic, and/or digital means. If this delayed sound is then phase-inverted and combined with that from the front microphone/microphone port, some cancellation or reduction in sound level will occur. The greatest reduction will occur for angles that result in approximately equivalent internal and external delays. Consequently, engineers can assign internal delay to better specify the angles of greatest sound attenuation. Important to note is that, since the amount of sound cancellation depends on the relationship between internal and external delay as well as the number of places sound is sampled in space, the theoretical directivity limits for the pressure gradient and dual microphone approached are identical.

A further potential advantage can be gained in specific situations by the introduction of adaptive directional systems. These systems are designed to adapt their attenuation pattern to provide attenuation to discrete sound sources in the rear hemisphere. However, the limitations related to the number of ports still hold. Therefore, the maximum directivity possible from an adaptive system will not exceed that of a traditional fixed-directional hearing aid for any single environment for which the fixed system has been optimized. Consequently, no additional directional benefit is usually expected from adaptive systems over their fixed counterparts in environments with multiple noise sources. Instead, an adaptive advantage may be seen in cases of noise that arrives from a fairly discrete angle, especially in cases for which the noise is placed to the side(s) of the listener. The design of modern directional hearing aids has been modified in that many current manufacturers "tune" the response of the directional microphone system in an attempt to provide maximum directivity across frequencies on the head. Consequently, directivity of modern hearing aids approaches theoretical limits [3]. Those readers interested in further details of directional microphone design in hearing aids are referred to the work of Thompson [4].

Further improvements in directivity have also been accomplished through the introduction of microphone arrays that use more than two microphones. In general, multimicrophone arrays have not enjoyed much commercial success, in part because of cosmetic factors. That is, the majority of arrays introduced to date have been large, limiting their commercial appeal. One exception, however, is the Siemens Triano 3. This instrument incorporates a three-microphone array in a standard behind-the-ear (BTE) case. Because of limitations related to low-frequency sensitivity when the microphones used in a directional array are spaced close together, the three-microphone array is only active for frequencies above approximately 800 to 1,000 Hz, with two microphones used to achieve directivity for the lower frequencies. Despite this limitation, use of the three-microphone array in high frequencies affords the possibility of slightly higher average directivity than is possible from two-microphone, or two-microphone-port, systems.

The interest in modern directional hearing aids began with the introduction of the first modern twin microphone system in the early 1990s, the Phonak Audiozoom™ (Staeta, Germany). Research revealed significant directional benefit in noisy environments with this device [5]. In 1997, Etymotic Research (Elk Grove Village, IL) introduced the D-Mic™. The D-Mic, a directional-plus-omni design, differed from previous directional microphones in that both the omnidirectional and directional microphones and microphone preamplifiers were housed within a single capsule. This design allowed for several hearing aid manufacturers to place a directional microphone in the faceplate of existing in-the-ear products.

Modern designs such as the two just mentioned helped lead to the resurgence in directional hearing aid use. In addition, the ability of directional hearing aids to improve speech recognition, in comparison with their omnidirectional counterparts—referred to herein as directional benefit—has been demonstrated in a variety of noisy environments [2–3,6–15]. The positive results of these studies have also been a major factor in the relatively recent increase in the prescription of directional hearing aids. Despite generally positive findings, however, data indicate that the magnitude of directional benefit can vary tremendously [3]. It should also be noted that the signal-to-noise ratio (SNR) advantage provided by directional microphones is much smaller than that possible by a reduction of the listener-to-microphone proximity (as with frequency modulation [FM] systems). However, FM systems may not be desirable or appropriate for all noisy situations, especially those with multiple talkers of interest. In such situations, directional hearing aids may be the preferred fitting.

A number of factors are responsible for the large variability in reported directional benefit. Aspects that affect the magnitude of directional benefit generally can arise from individual listener differences; fitting factors, such as vent size and microphone opening azimuth [3,10]; and environmental factors, such as reverberation, distance, and angle and position of the listener relative to sound and noise sources [11,16–18]. The breadth of listening environments experienced by listeners leads to outcomes ranging from approximately a 7 dB SNR directional advantage (albeit in somewhat contrived laboratory settings) to a directional disadvantage.

Past laboratory studies indicate that directional benefit will be approximately 2 to 3 dB in noisy environments that are similar to those experienced in the real world if several conditions are met:

1. No more than moderate reverberation occurs.
2. The listener is facing the sound source of interest and the distance to this source is within the critical distance (CD).*
3. The noise sources surround the listener.
4. The hearing aid has a directional microphone with high average DI values.

*Critical distance is defined as the distance from the source at which the intensity level from the direct and reflected portions of the source are equal.

This, of course, leads to the question of how often these conditions are met in the real world. While this question has not yet been fully answered, research related to these issues is discussed throughout the remainder of this article.

DESIGN AND FITTING FACTORS

As noted previously, the DI is used to acoustically quantify how well the directional hearing aid attenuates sound arriving from angles other than directly in front of the listener. The average DI measured on the head is useful in that differences in DI that have been averaged across frequency have been shown to correlate well with differences in speech recognition in noise performance [19]. Generally, the higher the DI, the larger the expected directional benefit. This relationship is not without limitations, however. Specifically, further increases in directivity may eventually provide no further benefit or may even be detrimental in some environments. Complaints related to “tunnel hearing” (not being aware of important sounds not directly in front of the listener) and limited low-frequency microphone sensitivity are associated with extremely directional microphone arrays. These potential problems highlight the fact that additional research related to the limits of useful directivity is still needed.

Specific hearing aid design parameters can also impact directivity (see Ricketts and Dittberner [3] for a review). Fortunately, design factors such as hearing aid style and the use of other signal-processing schemes such as compression generally have little impact on the magnitude of directional benefit [9,12]. One design factor that can indirectly impact directional benefit is hearing aid size or, more specifically, the spacing between the directional microphone ports. The directional microphone mode leads to a reduction in low-frequency microphone sensitivity. This reduction is due to the low frequencies that are more in phase than the high frequencies for the same sound arriving at the two microphone ports. The frequency at which the low-frequency roll-off begins is predictable based on the spacing between the microphone ports, with increasingly smaller separation resulting in the reduction in sensitivity occurring at increasingly higher frequencies. For frequencies below this point, the magnitude of low-frequency attenuation is approximately 6 dB per octave. In practice, the reduction in the low-frequency output of a directional hearing aid may be less because of

venting effects or gain compensation. An example of the difference in frequency response measured in the ear for one group of patients fit in omnidirectional and uncompensated directional modes is shown in **Figure 1**. This figure was derived from previously reported data [20]. Compensation for the associated low-frequency attenuation has been shown to be necessary for listeners to avoid reduced audibility with low-frequency hearing losses of greater than approximately 40 dB hearing level (HL) [20]. Gain compensation for listeners with little or no low-frequency hearing loss is not recommended, however, because of the potential increase in audibility of the low-frequency microphone noise floor.

The DI of a well-designed hearing aid can also be compromised by other fitting factors. Specifically, a reduction in DI will occur as vent size is increased and as the plane through the microphone ports deviates from horizontal. Fortunately, venting mainly impacts low-frequency directivity. Positive high-frequency directivity (above approximately 1,000 Hz) will be maintained, even in the case of an "open" earmold [10]. Deviations from the horizontal plane for the two microphone ports can be minimized with careful attention to marking the horizontal plane in the earmold impression for custom instruments and attention to tubing length in BTE instruments. In some cases, deviations from the horizontal plane are unavoidable because of comfort issues related to BTE tubing length and ear geometry in custom instruments. In such cases, clinical measurement of changes in directivity, such as those discussed in the following, are encouraged to ensure adequate directivity is still present.

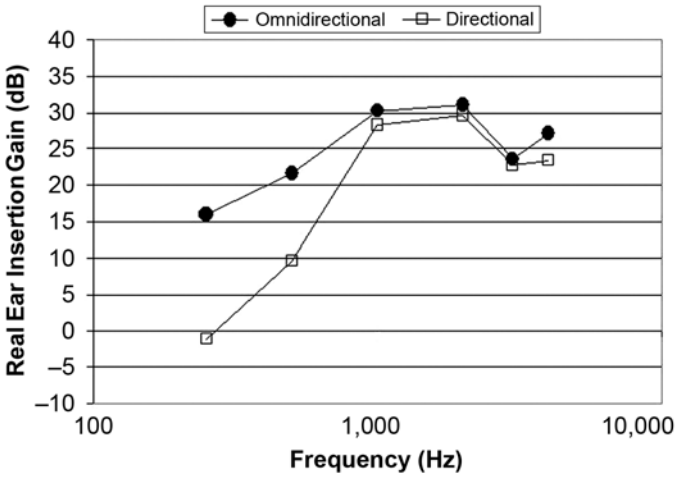

Figure 1.
Hearing aid output measured in ear for one group of patients fit in omnidirectional and uncompensated directional modes. *Source:* Ricketts T, Henry P. Low-frequency gain compensation in directional hearing aids. Am J Audiol. 2002;11:29–41.

REAL-WORLD LISTENING ENVIRONMENTS

Walden et al. assessed the proportion of listening environments for which directional benefit is expected [21]. Specifically, the listening environments in which 17 patients reported a preference for directional and omnidirectional hearing aid modes over a 6-week period were examined. Participants were asked to identify and describe at least one listening situation each day in which one of two user programs performed best using a checklist and daily journal format. Results of this study indicated that listeners reported a preference for the directional mode (assumed to be related to positive directional benefit) during about one-third of their active listening time. The environmental factors associated with directional preference were consistent with those identified in laboratory-based studies, namely, facing a talker who is near, in a room with moderate or less reverberation.

While it is clear that directional hearing aids can enhance speech understanding in some noisy environments, full-time use of this technology has not been recommended [22]. Data have revealed that directional hearing aids are usually not preferred in quiet, although pilot data in my laboratory indicate directional benefit is possible in extremely reverberant environments, but only in the *absence* of competing noise. Speculation related to reasons for the patient preference for the omnidirectional mode in quiet could encompass several areas; however, further work in this area is needed to positively identify important factors.

Data have also shown a directional disadvantage in some noisy environments, most notably those in which the source of interest is behind or to the side(s) of the listener. The directional hearing aid mode can also be problematic because of an increase in the susceptibility to wind noise [4]. Recently, hearing aids have been introduced with multichannel directivity in an attempt to offset this problem. The expectation is that multichannel directional hearing aids will automatically switch to an omnidirectional mode in the low frequencies to offset the increase in perceived wind noise associated with directional microphone use. Recommendations for directional microphones are also tempered by their SNR limitations.

If a listener requires a +15 dB SNR to understand speech and is routinely in environments in which the SNR is +3, a directional hearing aid mode will not provide enough of an increase in SNR to be beneficial. In such situations, especially when it is important to understand the speech of a single talker, other assistive listening devices such as FM systems are advocated [23].

Since full-time use of the directional hearing aid mode may be problematic, hearing aids commonly include both directional and omnidirectional modes. Clinical and research experience indicates this solution can work quite well for listeners capable of switching at appropriate times. For listeners who are unable or unwilling to switch, an automatic directional hearing aid may be an option. That is, the automatic directional mode may be appropriate for children, those with very poor dexterity, or those who view switching as especially inconvenient. Automatic directional hearing aid systems use one or a series of "decision rules" to determine when best to switch between directional and omnidirectional modes. Unfortunately, hearing aids are not able to read a patient's mind, and automatic directional hearing aids are not currently always capable of making the correct switching decision.

CURRENT RESEARCH IN DIRECTIONAL HEARING AIDS

Work examining directional hearing aids continues in my laboratory on several fronts. Most recently, we have been examining the impact of listener age and degree of hearing loss on directional hearing aid use and benefit. In addition, work continues on our attempts to quantify average directional benefit based on specific hearing aid and environmental factors. Related to age, we have focused on the viability of directional hearing aids for school-aged children. Limitations to directional benefit that are specific to children include, but are not limited to (1) concern over their ability to appropriately turn their head toward the sound source of interest, (2) their potentially limited experience with receptive speech, and (3) the importance of overhearing secondary sounds in their environment. Our work to date examines whether children as young as 4 years old orient their heads toward the sound source of interest in real classroom environments. In the second phase of this study, we are examining whether children receive directional benefit in common noisy environments. Preliminary data show significant variation but suggest that whether children orient their heads correctly or not most highly depends on the specific listening task [24]. Additionally, as with adults, apparently directional benefit will be achieved in some noisy listening environments but not others. Further, directional hearing aid use may be detrimental in some noisy listening environments. Not surprisingly, the environmental factors that affect directional benefit in adults also appear to affect directional benefit in children.

DEGREE OF HEARING LOSS

Degree of hearing loss is also of significant interest. Previous research has suggested that predicting the magnitude of directional benefit an individual will receive based on common audiometric factors is difficult [25]. Our most recent work, however, indicates that the magnitude of directional benefit obtainable will likely be limited in listeners with severe to profound hearing loss. Currently, we are examining directional benefit in adults with symmetrical, severe to profound hearing impairment. All participants to date have exhibited pure-tone average hearing thresholds of 65 HL or greater. All participants are fit bilaterally with commercial power BTE hearing aids in both directional and omnidirectional modes. We matched gain in the directional mode as closely as possible to that provided in the omnidirectional mode to offset any differences in audibility. The test environment is a 10.5 ft^2 (6 ft 7 in. high) sound-treated booth that was modified with reflective panels to provide the following reverberation times: 250 Hz = 485 ms, 500 Hz = 440 ms, 1,000 Hz = 400 ms, 2,000 Hz = 310 ms, and 4,000 Hz = 220 ms. A single speech loudspeaker (Tannoy System 600, Coatbridge, North Lanarkshire, UK) and five uncorrelated competing noise loudspeakers surround the listener (Definitive Technologies BP-2x, Owings Mills, MD). All sound sources are placed 1.25 m from the listener. Listeners are seated in the exact center of the test room. This configuration is identical to that used previously to assess directional benefit in listeners with mild to moderately severe hearing loss (e.g., Ricketts et al. [12]). We assess performance in directional and omnidirectional modes using the Connected Speech Test [26] at three different SNRs and in quiet using both audio only and audio plus visual presentations of the test. The exact SNR is chosen for each patient individually so we can obtain a three-point performance/SNR function

in both directional and omnidirectional modes while avoiding ceiling and floor effects. Specifically, the SNR of a practice list is adjusted for both audio only and audio plus visual presentations to a level at which participants report they can still understand just a few words in omnidirectional mode.

An example of typical performance for the audio only condition is shown in **Figure 2**. This figure shows that directional benefit was greatest (13%) at the poorest SNR (+8 dB) and was essentially absent at more positive SNRs. This pattern of directional benefit, as well as the magnitude of maximum directional benefit, is typical for those participants measured to date. In comparison, Ricketts et al. reported that listeners with moderate hearing loss received approximately 25 to 30 percent directional benefit in the same listening environment (albeit at poorer SNRs) [12]. Notably, our data also support similar DI values measured across the instruments used in these two investigations. I propose that one likely cause for the limited directional benefit measured in many listeners with severe to profound hearing loss is the SNR of presentation. Specifically, previous research suggests that speech minima fall approximately 15 to 18 dB below average speech levels (see Amlani et al. [27] for a review). Consequently, as the SNR approaches +15 dB, any further improvement in SNR is expected to have a limited impact on performance. This limitation is supported by **Figure 2**, in that performance in quiet only exceeds omnidirectional performance at the poorest SNR by approximately 26 percent and by only 10 percent at the best SNR, greatly limiting the magnitude of directional benefit that is possible. Even greater directional benefit might be expected for this patient when evaluated at SNRs poorer than +8 dB; however, such measures are not possible because this SNR corresponded to the performance floor in omnidirectional mode. The role of audibility in the limited directional benefit demonstrated by listeners with severe to profound hearing loss is further supported by Ricketts et al. [19]. Specifically, results of this study revealed that limited directional benefit would be expected for listeners with profound hearing loss, given Speech Intelligibility Index calculations based on tested speech and noise levels if hearing loss desensitization was also accounted for.

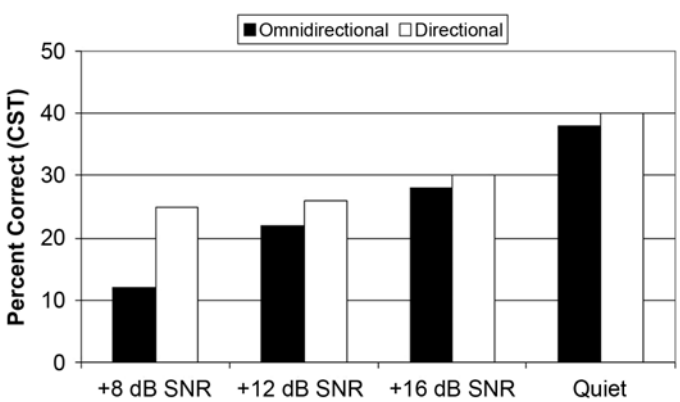

Figure 2.
Performance of single listener for both directional and omnidirectional modes for three different signal-to-noise ratios (SNRs) and quiet presentations of audio portion of Connected Speech Test (CST). This listener had pure-tone average hearing threshold of 70 dB hearing level.

ENVIRONMENTAL FACTORS

Work also continues that examines prediction of average directional benefit based on environmental factors. Ricketts and Hornsby examined the impact of speaker-to-listener distance on directional benefit in two reverberant environments [17], in which the dominant noise sources were placed close to the hearing aid wearer. Specifically, the aided sentence recognition in noise for 14 adult participants with symmetrical sensorineural hearing impairment was measured in both directional and omnidirectional modes. A single room containing four uncorrelated noise sources served as the test environment. The test environment was 4.0 m wide × 5.0 m long × 3.2 m high. The room was modified to exhibit either low (RT60 [the time a signal takes to decay to 60 dB] = 0.3 s) or moderate (RT60 = 0.9 s) levels of reverberation. Sentence recognition was measured in both reverberant environments at three different loudspeaker-to-listener distances for the speech source (1.2, 2.4, and 4.8 m). CD was approximately 2.2 m in the moderately reverberant environment. In situ Speech Transmission Index (STI) measures obtained through the test hearing aid fitted to a Knowles Electronic Manikin for Acoustic Research (known as KEMAR, an anthropomorphic manikin whose dimensions were designed to equal those of a median human) were also made in each of the 12 listening conditions (2 microphone modes × 3 distances × 2 reverberation environments). Surprisingly, the results revealed significant directional benefit was still present (although reduced) in the moderately reverberant environment at the farthest speech speaker-to-listener

distance tested in this experiment. This was unexpected, given the expected effect of the directional microphone on the sound energy from the speech source placed beyond the CD. Directional hearing aids generally provide benefit by providing less output for sounds arriving from the rear than for sounds arriving from the front. That is, they provide attenuation to the reverberant sound energy relative to the sounds arriving from directly in front of the listener as quantified by the DI. Consider only the speech source placed in front of the listener. The angle of arrival for sound originating from this source at greater distances (beyond CD) is dominated by reflected energy. That is, the dominant energy will not arrive from the angle of the source origin but rather from multiple angles. Consequently, the directional microphone will provide attenuation to the overall source energy. Despite this surprising result, notably, the pattern of average sentence recognition results across varying distances and two different reverberation times agreed with the pattern of STI values measured under the same conditions.

The work of Ricketts and Hornsby [17] was most recently extended to examine both the impact of speaker-to-listener distance in the presence of noise sources that were distant from the listener and the impact of an adaptive directional mode. The adaptive directional mode was generally designed to automatically adjust the pattern of directional attenuation to maximize the attenuation for any discrete sound source arriving from the rear hemisphere. In this study, the word-recognition performance of binaurally aided listeners was measured under omnidirectional and adaptive directional microphone modes in eight listening conditions. A single room with moderate levels of reverberation (RT60 = approximately 0.9 s) again served as the test environment. Two different speech-loudspeaker-to-listener distances (1.2 m and 4.8 m) were selected from the previous experiment and represent distances that are well within CD and well beyond CD for both omnidirectional and directional microphone modes. Two separate competing noise loudspeaker configurations were evaluated. Masking configuration 1 included four uncorrelated, competing noise loudspeakers placed in the corners of the listening room (approximately 3 m from the listener and well outside CD). Masking configuration 2 was identical to masking configuration 1, except that an additional loudspeaker was placed directly behind the listener (180° azimuth) at a distance of 1.2 m (within CD). This configuration was intended to simulate common listening environments in which competing sources are both near and far.

Data to date further support the predictability of the relative magnitude of directional benefit in the test environment from STI measured through the test hearing aids in the specific listening environments. Work continues that is aimed at examining the validity of using in situ STI measures for prediction of the relative magnitude of directional benefit across different SNRs, speaker-to-listener distances, reverberation times, and hearing aid directional sensitivity patterns.

INTERACTION BETWEEN BINAURAL AND DIRECTIONAL AMPLIFICATION

Both directional microphone hearing aids and bilateral amplification can enhance speech-recognition performance in noise with hearing-impaired listeners. A few studies have examined whether these benefits are additive in nature. Ricketts [16] evaluated speech recognition in noise performance for 20 listeners fit monaurally and binaurally with BTE hearing aids set in both directional and omnidirectional modes using the Hearing in Noise Test (HINT) [28]. The HINT is a task in which one adaptively varies the SNR by adjusting the speech level. The nature of this task provides results that are quantified as the decibel level for which the listener can still repeat sentences with 50 percent accuracy. Consequently, *lower* SNR scores represent better performance. All listeners exhibited symmetrical, sloping, and sensorineural hearing loss.

While the primary focus of this investigation was to examine the impact of head and body angle on directional benefit, the data collected for conditions in which the listener was directly facing the sound source of interest provide information related to directional and binaural benefits in a noisy environment. Sentences from the HINT were presented with a background of five spatially separated, uncorrelated samples of cafeteria noise. All testing was performed in a moderately reverberant (RT60 = 631 ms) environment. The results of this investigation provided additional support for directional and binaural benefit in noisy environments. Interestingly, the magnitude of these advantages was similar to that reported in previous investigations and the directional benefit and binaural advantage were relatively independent. The binaural advantage averaged 2.3 and 2.5 dB for directional and omnidirectional

modes, respectively. The directional benefit was 3.8 and 4.1 dB for the monaural and bilateral conditions, respectively. The lack of significant interaction between microphone and monaural/bilateral conditions supports the additive nature of these two benefits. In total, average HINT performance improved 6.4 dB when monaural omnidirectional and binaural directional conditions were compared.

The impact of bilateral fitting on directional benefit has more recently been investigated by comparison of a bilateral directional fitting to a bilateral fitting in which one hearing aid is in the directional mode and one is in the omnidirectional mode [29]. In this study, the HINT sentence-recognition thresholds were obtained from 16 subjects with mild to severe sensorineural hearing loss in three noise source configurations, including (1) speech at 0° and a relatively "diffuse" cafeteria babble surrounding the listener, (2) speech at 0° and cafeteria babble on the left side of the listener, and (3) speech at 90° (the right side of the listener) and traffic noise on the left side of the listener. Performance in each noise configuration was assessed in four hearing aid conditions: (1) omnidirectional in both ears, (2) directional in both ears, (3) omnidirectional in the left ear and directional in the right ear, and (4) directional in the left ear and omnidirectional in the right. The results of this study revealed that directional benefit was present in noise configurations 1 and 2, and the directional mode provided a disadvantage in listening configuration 3. For noise conditions in which directional benefit was present, a directional advantage was seen across all three hearing aid configurations. Significantly more (approximately 1.2–1.5 dB) directional benefit was present for the bilateral directional condition when compared with the conditions with one omnidirectional aid. These results are in apparent conflict with recent data from Bentler et al. [30], which revealed no significant differences in performance between bilateral directional and bilateral directional/omnidirectional conditions. The presence or absence of an interaction between bilateral and directional benefit may depend on the specific test conditions including possible interactions between source location and the specific hearing aid spatial attenuation pattern. Regardless, the use of bilateral directional mode is apparently beneficial in at least some listening environments.

Work has also begun on the possible impact of microphone mode on bilateral localization abilities. In a recent study, Henry and Ricketts examined auditory localization accuracy in the lateral horizontal plane for nine listeners with impaired hearing [31]. Auditory localization accuracy was measured in three listening conditions, including unaided and the bilaterally fitted BTE hearing aids in omnidirectional and directional microphone modes. Listeners reported the perceived location of a narrow band of noise centered at 4,000 Hz. The authors speculated that directional sensitivity patterns that deviated from that of the unaided ear would correspond with poorer localization accuracy since none of the listeners had prior experience with BTE hearing aids. While considerable variability existed, the results generally supported this hypothesis. Specifically, localization accuracy was significantly poorer in the aided conditions (those with disrupted interaural level difference [ILD] cues) than in the unaided condition. Localization accuracy for the two aided conditions, however, was not significantly different.

CLINICAL IMPLICATIONS

Despite advances in hearing aid technology, our primary focus must always return to recognizing our patients' individual abilities and needs. We must evaluate the type of listening environments to make more accurate predictions related to directional hearing aid benefit. The information should include an estimate of the SNR (+5 to –10 dB is common in real-world environments), the location and distance of the sound source of interest, and the dominant noise sources [32]. This can be evaluated informally or in combination with the formal use of tools such as the Client Oriented Scale of Hearing Aid Improvement with adult patients [33]. With children, formal scales such as the Listening Inventories For Education [34] and/or information about typical listening environments from parents and teachers can be used.

Once this information is known, the SNR at which a patient can perform adequately may be evaluated (e.g., with the QuickSIN [Quick Speech-in-Noise test] [34] or HINT). This information can then be combined with SNR knowledge of listening environments that are important to the individual patient for an estimation of the directional benefit in those environments. This decision-making process is demonstrated in **Figure 3**, which presents two hypothetical patients. Clinically, Patient A presents a score on the HINT of 0 dB SNR (or similar adaptive sentence-recognition-in-noise test). Patient B presents a HINT score of +13 dB SNR. Given an 11 percent change for every 1 dB change in

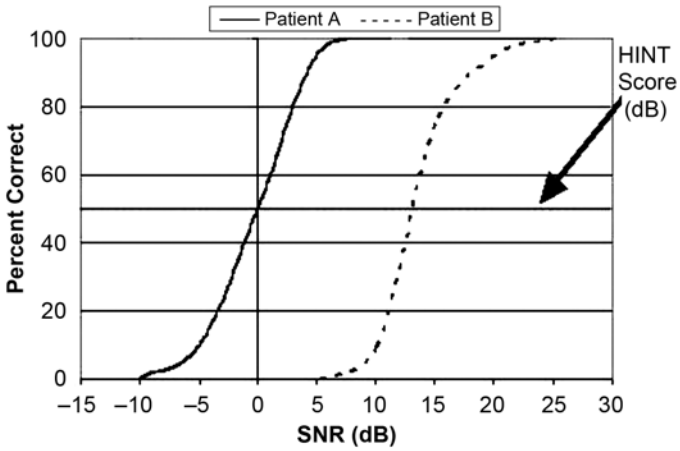

Figure 3.
Change in performance as function of signal-to-noise ratio (SNR) for two hypothetical patients. HINT = Hearing in Noise Test.

the HINT scores [35], the performance/SNR corresponding to the solid and dashed lines in **Figure 3** would be expected. Let us further assume that each of these patients is fit with a directional hearing aid that has an average DI approximately 6 dB higher than its omnidirectional counterpart. In other words, one expects that the directional mode will improve the SNR by as much as 6 dB. It follows that this 6 dB will provide the most benefit to Patient A for listening environments that have an SNR ranging from about –3 dB to about +3 dB. In contrast, Patient B will obtain the most benefit in listening environments that have an SNR ranging from about +10 dB to about +16 dB. In other words, both patients may receive significant directional benefit, but the environment for which they obtain benefit will differ greatly with respect to SNR. In addition, the potential for directional benefit will also be less for listeners as SNRs approach +15 dB, as discussed previously. Consequently, other interventions, such as FM systems, may be much more appropriate than directional microphones for listeners with this magnitude of aided SNR loss. Given the large magnitude of SNR improvement possible through FM systems compared with directional hearing aids, these systems may be the most appropriate intervention in many listening situations. This is especially true in situations with only a single talker of interest.

Also clinically important is informally assessing whether patients can switch between directional and omnidirectional modes. If they are not, the decision rules used by the automatic directional hearing aid must typically be appropriate for the listening environments important to patients. Consequently, clinical knowledge of the specific decision rules used for automatic directional mode in the hearing aid being fit is critical. Such rules may range from a simple rule that switches to directional mode whenever the total signal level reaches a predefined level to complex rules that weigh the total signal level, the signal levels at the output of the directional and omnidirectional modes, and the modulation pattern of the signal.

Clinical assessment of the directivity of the hearing aid being fit is highly recommended for quality control and for assessing the impact of fitting factors. Clinical assessment of directivity can be accomplished through measurement of the front-to-back ratio (FBR). This measure is useful for quantifying that the directional microphone works properly, as well as serving as a benchmark against which future measures can be compared. The specific measurement method for the FBR differs slightly across probe microphone measurement equipment. Generally, however, the frequency-specific FBR is calculated as the difference between the real ear aided response (REAR) measured with the test speaker at a fixed distance at an angle of 180° (directly behind the hearing aid wearer) and the REAR measured in response to the same test signal and distance, but at 0° azimuth (directly in front of the listener). Some probe microphone systems have specific software for calculation of the FBR; however, it can also be calculated with any system capable of measuring real ear insertion gain (REIG). Specifically, saving the REAR measured at 180° as the real ear unaided gain and the REAR measured at 0° as the REAR will lead to a “REIG” difference calculation that is actually the FBR expressed in terms of positive numbers. It is often easiest to leave the speaker in a stationary position and place the patient on a rotating chair to obtain the two measures. Consistent distance from the loudspeaker to the hearing aid microphone across the two measures can easily be ensured through the use of a piece of string tied to the loudspeaker. The impact of low threshold compression on the magnitude of the measured FBR should also be considered. While a discussion of this interaction is beyond the scope of this article, the interested reader is referred to Voss [14] for a complete discussion of this topic. Clinical measures of directional benefit may also be useful for quality control and counseling; however, recent data suggest that directional benefit measured in the clinic with a single noise source do not correlate well with perceived directional benefit in the real world or with use of the directional mode [36].

In addition to candidacy for directional hearing aids, the issue of bilateral candidacy should also be considered. Given clear binaural advantages related to localization and speech understanding in noise present for many listeners, bilateral fittings continue to be advocated for the majority of hearing aid candidates. Simon et al. have recently shown that although most listeners with moderate hearing losses have good to excellent accuracy of localization, unfortunately, some will always have difficulty localizing sound, possibly as a result of monaural amplification or poorly fit bilateral hearing aids.* In addition, the decreased localization ability may be seen in the unaided situation, especially with monaurally fit individuals. It is also interesting to speculate if and how directional processing impacts localization. It is well accepted that binaural localization is made possible through differences in the level and timing between the ears (ILDs and interaural time differences), as well as spectral shape differences resulting from Pinna effects. Since the directional mode intentionally affects hearing aid output based on spatial location, one might speculate that the resultant changes in the ILD cues may negatively impact localization, especially in the case of high-frequency-band-limited stimuli. While further work is still needed, preliminary data discussed earlier suggest similar localization performance for novice hearing aid wearers in directional mode to an unaided condition for very narrow bandwidth high-frequency signals [31]. Interestingly, this same study revealed reduced localization in omnidirectional mode. Based on the work of Byrne et al. [37], however, I hypothesize that any degradation in localization due to a fixed change in ILD cues that results from microphone effects might be overcome with enough experience. In addition to a general recommendation for bilateral hearing aid use, it appears that data support the use of the directional mode bilaterally, rather than directional in one ear and omnidirectional in the other for at least some listening situations. Therefore, the optimal directional fit appears to be bilateral, at least for those listeners expected to benefit from binaural amplification and able and willing to switch microphone modes appropriately.

Finally, appropriate counseling is recommended related to use. Simple recommendations such as always switching to the directional mode when in a noisy room would not appear to lead to optimal use of this technology. Issues related to talker-to-listener distance, facing the sound source of interest, orientation so that the primary noise sources are behind the listener, and experimenting with the directional and omnidirectional microphone modes in a variety of listening situations should be discussed with hearing aid wearers who are sophisticated enough to use this training appropriately.

CONCLUSIONS

The prescription of directional hearing aids has greatly increased in the past several years. Logically, nearly all hearing aid wearers are likely to gain some benefit from an increase in SNR. Therefore the majority of listeners are expected to achieve directional benefit at least in some listening situations. However, one should note that the magnitude of this benefit (quantified as improved speech recognition in noise) may be small in many realistic environments (perhaps 10%–30%) and may not necessarily be noticed by some listeners. The presence of a perceived general advantage from the directional hearing aid mode for individual listeners will also depend on the interaction between at least three additional factors: (1) the SNRs of the environments that are important to the listener, (2) the SNR range over which the listener is able to adequately recognize speech, and (3) the ability of the listener or automatic switching processing to choose the appropriate microphone mode. Simply stated, listeners who do not generally experience environments in which a 4 dB to 6 dB increase in SNR will improve speech-recognition performance will probably not perceive a directional benefit. In some cases, the listener may require an FM system or other assistive listening device in lieu of a directional microphone to provide an adequate SNR.

Use as well as candidacy must be considered relative to directional hearing aids. That is, the directional mode is not advocated for full-time use and counseling related to proper use is necessary in most cases. For patients who meet the criteria for directional candidacy, benefit is only expected, and use of the directional mode is only advocated, for specific situations. Data reveal that, minimally, the listener should face the signal of interest in proximity to obtain directional benefit. In addition, the noise must either surround the listener or be concentrated behind the

*Simon HJ, Levitt H, Lotze A. Localization ability using a continuous paradigm: Symmetric sensorineural hearing loss. Unpublished observations; January 2005.

listener. Further investigations should allow for the prediction of average directional benefit in any environment, perhaps leading to more accurate automatic switching algorithms. Further work is also needed to define all potential limitations to directional technology, including the potential impact on localization. I hope that basic and clinical research regarding these issues will continue on the present scale.

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