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The Evolution of Directionality: Have Developments Led to Greater Benefit for Hearing Aid Users?

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The evolution of directionality can be described as a step-by-step process where more complex algorithms have been developed over time. This article looks at how each development step differs from traditional fixed directionality, explains how different directional features work, and gives clinical advice for each. In addition, accessories that can further improve SNR via wireless communication are discussed.

Directionality in digital hearing aids has evolved in the last 15 years from hearing aids with fixed directional patterns to the many directional options available today. Directionality in the most basic form has the benefit of improving the signal-to-noise ratio (SNR) for hearing aid users. The question posed in this paper is if newer developments have led to greater end-user benefits? The answer is only if clinicians completely understand each directional feature and how to accurately select, fit, and counsel patients about the proper use.

This article discusses the evolution of digital directionality, explains how different directional features work, and most importantly gives clinical advice for each. In addition, accessories that can further improve SNR via wireless communication will be discussed.

The Need to Understand Directionality and Its Applications

Individuals with hearing impairment not only have hearing loss (or loss of audibility)—which is compensated for through amplification in hearing aids—but they also have increased difficulty hearing in noise, or SNR loss. To provide better hearing in noise, modern digital hearing aids incorporate two microphones and the use of digital signal processing to create directional algorithms that improve the SNR for users of hearing aids by attenuating sound from some directions while emphasizing it from others.[1-3]

Good Candidates for Directionality

Listeners with SNR losses, especially those with SNR losses in the mild-to-moderate range (4-8 dB SNR loss), can benefit from directional algorithms when listening in many noisy environments. For those with greater SNR losses, directionality can still provide the benefit of listening comfort and can help with understanding of speech in noise as long as contextual and speech cues are available.

Over the last 10 years, many new directional features have been introduced in digital hearing aids. These include, but are not limited to, adaptive directionality, steering of directional patterns, and asymmetric directionality. These features need to be understood by both the dispenser and end user so they can be used appropriately.

Patients Who Need Even More

In addition, listeners with SNR losses greater than 8 to 10 dB or listeners in environments with very poor SNRs can benefit from devices that provide even greater SNR improvement. Some wireless hearing aids are available with microphones that can be worn by a speaker so their voice can be streamed directly to the hearing aid user’s ear. These newer technologies conveniently improve the SNR beyond the performance of directionality in hearing aids alone.

The evolution of directionality can be described in a step by step process where more complex algorithms have been developed over time. The focus here will be on how each development differs from traditional fixed directionality and when it should be used.

Step 1: Digital Directionality

Although hearing aids incorporating directionality were available on the market before the 2000s, the digital hearing aids introduced with directionality in the early 2000s had higher directivity indices (DIs) and the ability to switch between omnidirectional and directional settings. These aids represented the first step in the modern evolution of digital directionality, and the improvements ultimately provided greater overall end-user benefit and led to the acceptance of directionality as an important feature in hearing aids. In fact, Kochkin[4] pointed out that directional hearing aids were rated 17% points higher on consumer satisfaction surveys when compared with omnidirectional only hearing aids.

Figure 1 shows a schematic of how first-order directionality is achieved using two microphones in a digital hearing aid signal processor.[5] Sound enters the microphones where the acoustic energy is converted to electrical energy. Following electrical conversion, the two signals are sent through an electrical network where a time delay is applied to the rear microphone signal. Finally, the two signals are subtracted to produce directivity. When both microphones are active, a directional pattern is achieved. When an omnidirectional condition is desired, the rear microphone is shut off.

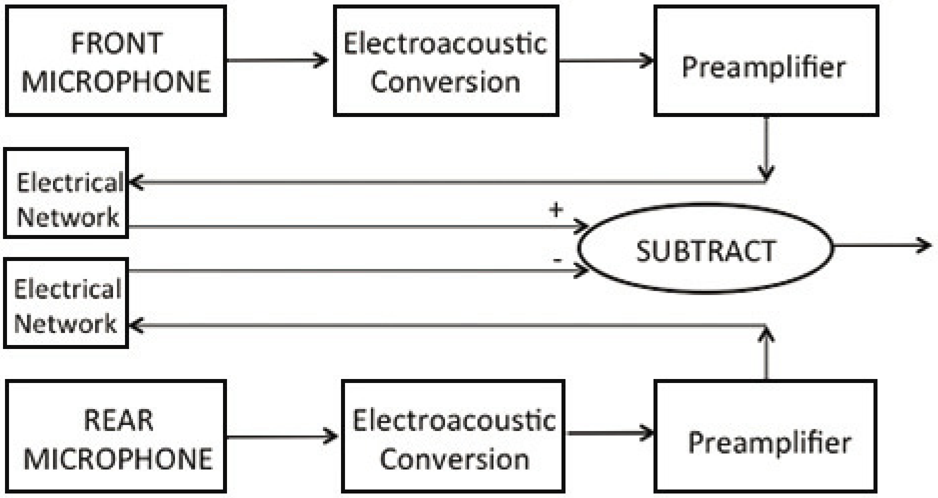


Figure 1. A schematic of how first-order directionality is achieved using two microphones in a digital hearing aid signal processor (adapted from Thompson[5]). By subtracting the electroacoustically converted and amplified signals from the front and back microphones, directivity patterns as shown in Figure 2 are created. When an omnidirectional response is required (ie, the majority of the time), the rear

microphone is shut off.

A variety of spatial directional patterns can be achieved using this method by changing the time delay applied to the signals. Figure 2 shows the most popular *fixed directional patterns*. When the nulls (points of maximum attenuation) are always at the same angle of the pattern and do not change depending on the location of noise or frequency, they are called fixed directional patterns. In this first step in the evolution of digital directionality, these patterns were fixed and directional to the front of the listener. The difference in the spatial patterns is mainly the location and depth of the null points.

From the polar plot, a measure called the *directivity index* (DI) can be obtained for individual frequencies. The DI is a number that represents how sensitive a microphone is to sounds arriving from the front relative to sounds arriving from other directions. An omnidirectional microphone has a DI of 0 dB when measured in a test chamber. Directional microphones in hearing aids have DIs that commonly range from 2 to 6 dB measured in the test chamber.

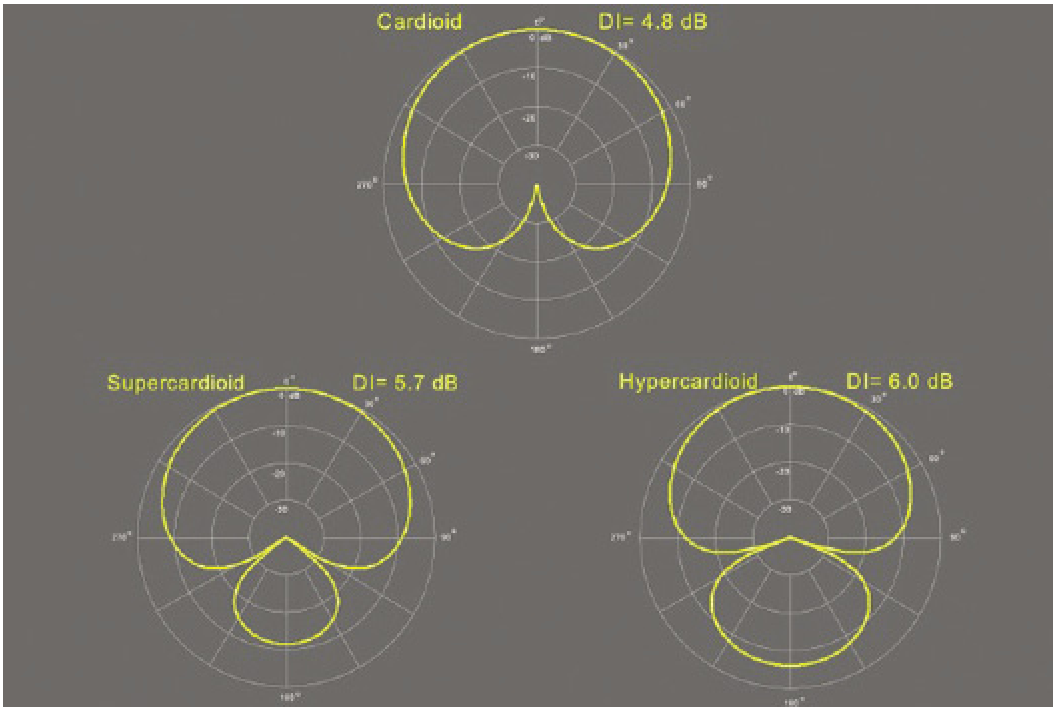


Figure 2. Examples of common directional polar patterns.

Measured in real-life situations, directional microphones in hearing aids improve the signal-to-noise ratio of sounds arriving from the front by approximately 3 dB. This SNR improvement can be higher when most noise is to the rear of the listener.[1,2]

Clinical Advice

1. Understand that these first-order directional microphones improve SNR by about 3 to 4 dB.
2. Measuring a patient's SNR loss using the Quick SIN or HINT test can be helpful to counsel a patient regarding *how much difficulty they will still have in noise when directional microphones are used*. Those with greater SNR losses (approximately 8 dB or larger) will require solutions with greater directivity.
3. Directionality is most effective when the signal of interest is in front of the listener and within 10 feet or the critical distance.[6] Beyond this distance, directional microphones do not provide significant benefits. Patients need to be counseled to consider the signal they want to hear and position themselves within 10 feet or less when possible.
4. Directional microphones work best when the noise and signal of interest are spatially separated

(coming from different directions).

Step 2: Digital Directionality with Automatic Switching

The first digital hearing aids equipped with directionality had a separate memory for the directional feature, and users had to manually switch to this program in a noisy environment to get the benefit of directionality. Cord et al[7] indicated that 30% of users did not switch between the settings and often did not know when to switch and/or did not want to do this manual switching in everyday life.

To overcome this manual switching problem, automatic switching hearing aids were introduced where the hearing aid automatically changes from an omnidirectional setting to a directional setting depending on the environment. These types of switching algorithms depend on environmental classification systems within the hearing aids, which analyze the acoustic scene and make a decision about which microphone mode would be most beneficial.

Thus, these systems are limited by the accuracy of the classification system and have no ability to determine the hearing aid user’s intent in complex listening situations. That is, the hearing aid assumes that the signal the user wants to hear is directly in front of them.

Clinical Advice

1. Automatic switching can be convenient, but the hearing aids equipped with this feature do not always switch to directionality when needed. For this reason, a memory with directionality always activated is helpful for some listeners. A hearing aid user willing to switch manually should be counseled that, if they are having trouble in noise in the first memory with auto switching, they can switch to the full-time directional program to see if it gives an improvement.
2. When hearing aids are in directional settings, listeners can no longer hear clearly signals to their sides and back; thus, they are limited to hearing what is in front of them. Since the hearing aid user might not always want to hear just what is in front, automatic switching like this can be problematic. Again, patients need to be counseled that the signal they want to hear should be in front of them. That means they might have to reposition themselves to achieve the directional benefit in a noisy situation.

Step 3: Adaptive Directionality

The next step in digital directional evolution was the introduction of adaptive directionality. This type of directionality differs from fixed directionality in that the null can be moved to the angle where the most noise is detected in the environment, thus adapting the attenuation to the specific environment. This can even be done at different frequencies (within each hearing aid frequency band) such that a hearing aid might have different directionality patterns depending on the frequency and location of the noise in the environment.

Many hearing aids today come with adaptive directionality. The benefit of this type of directionality is that, when a listener is in an environment where most if not all the noise is coming from a particular location, the hearing aid can put the point of maximum attenuation at this location creating a larger SNR improvement. In situations where noise is more diffuse (eg, a cocktail party or reverberant environment), the hearing aid adjusts to a fixed pattern.

Clinical Advice

1. Hearing aids with adaptive directionality can be more beneficial to hearing aid users than fixed directionality in certain environments. These environments include those in which the dominate noise source is originating at one specific location—for example, a noise source on the left side

of the hearing aid user. In this case, the adaptive directional pattern will steer the null point to the left so that the noise source is provided the maximum attenuation. The only time this would equal a fixed directional setting would be when the null happens to be at this same location angle.[8]

2. When noise is more diffuse in the environment, adaptive directionality provides the same benefit as fixed directionality.
3. Adaptive directionality is a good choice since it can both provide fixed patterns but also adapt the pattern when noise is not diffuse.
4. Note that many hearing aids use adaptive directionality as their default directional settings and combine this with automatic switching. This is the most common directional choice by default in modern digital hearing aids.

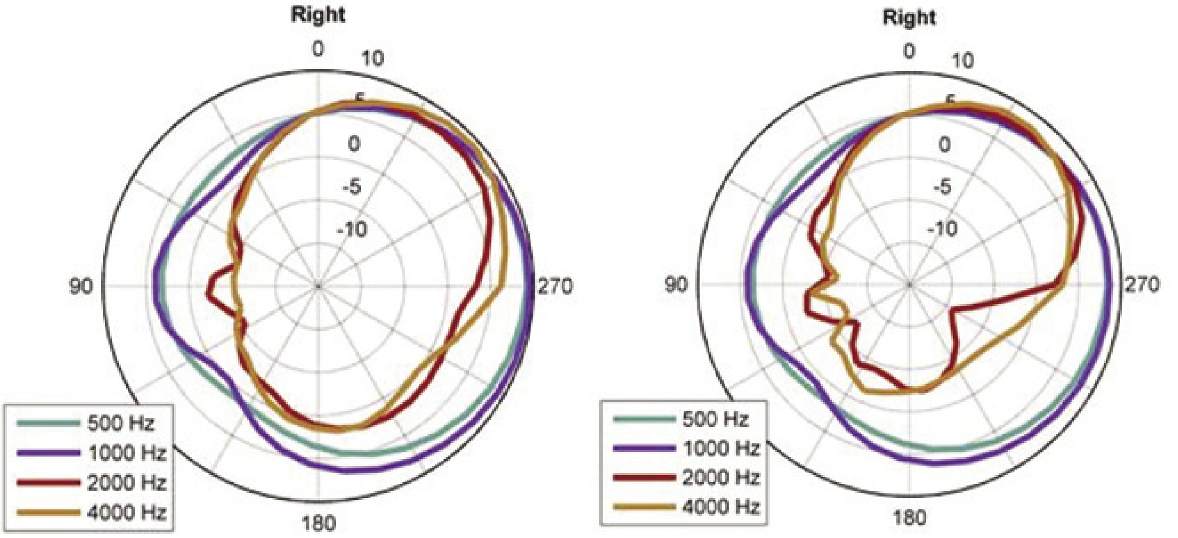
Step 4: Band-split Directionality

Creating directionality in a hearing aid inherently alters the frequency response of the aid. Specifically, the directional response has a low frequency roll-off that begins around 2000 Hz because low frequency sounds have a similar phase relationship between the front and rear microphones.

To compensate for the decrease in audibility caused by this roll-off in the directional setting, a boost in low frequency amplification is applied. This is called *equalization*. Equalization causes the internal noise floor of the hearing aid to increase, and ultimately it can detract from the benefit of the directional setting.[9] However, the result of *not* compensating for this low frequency roll-off is a tinny hearing aid sound quality in the directional setting and/or under-amplifying the low frequencies for those with low frequency hearing loss. Thus, traditional designs have the trade-off of being either too noisy or too tinny rather than sounding natural.

A solution for this problem is to process the sound in the hearing aid the same way it is processed by a normal-hearing listener. This processing, called split-band directionality, approximates the unaided ear’s natural directional characteristics.

Figure 3 illustrates how the open ear and *split-band directionality* are similar. The KEMAR response for four frequencies is shown on the left in the polar plot. For the two lower frequencies (500 and 1000 Hz) in the open-ear polar plot (left panel), the response is essentially omnidirectional while the higher frequencies are directional to the front. The panel on the right presents the same measurements performed on a hearing aid with split-band directionality. There is a good match between the split-band directional response and those of the open ear. Processing sound in a hearing aid this way results in more natural sound quality for the end user, but preserves the directional benefit of traditional directional settings.



Open ear

Split-band Directionality

Figure 3. Directional responses of the open ear on the left and split-band directionality on the right. Note that the two lower frequencies are more omnidirectional while the two higher frequencies are heard more directional with attenuation to the sides and back.

Split-band directionality provides a directional pattern closer to a person's open ear, thereby striking a natural balance between environmental awareness and directional advantage. Groth and colleagues[10] summarized the results of three studies investigating the effect of directional processing on sound quality. All three investigations used a double-blind design in which hearing-impaired listeners expressed a preference for split-band directionality, omnidirectional processing, or a traditional directional response. Listeners indicated an overwhelming preference for the sound quality of omnidirectional processing over traditional directional processing, and preferred split-band directionality over traditional directionality more than twice as often.

An additional advantage of processing sound in a split-band manner is the spectral preservation of the low frequencies, allowing the listener to take advantage of the natural ear timing differences that are important for sound localization. A recent study by Keidser et al[11] showed that interaural time differences (ITDs) are the most important cue to preserve for localizing sounds. In fact, the results indicated that interaural intensity differences (IIDs) could be mismatched up to 9 dB by compression in the hearing aid and not affect localization performance as long as some ITD cues were available.

These important ITDs are maintained in the split-band approach as evidenced in a recent article from Groth and Laureyns.[10] They reported on a study that examined the effect of different directional processing schemes on left/right and front/back localization performance of hearing-impaired listeners. The results showed that localization ability was maintained relative to the open ear using split-band directional processing.

Finally, one final benefit of band-split directionality that deserves mention is that it also solves the problem of over-amplification and distortion of near-field signals, such as one's own voice or wind noise in traditional directional settings. Again, equalization in a traditional hearing aid can make these signals distorted; using omnidirectional settings in the low frequencies does not cause this overamplification leading to distortion.

Clinical Advice

1. Band-split directionality allows for better sound quality while also preserving localization cues when listening in the directional hearing aid setting and still delivers good directional SNR improvement to end users. This type of directionality should be seriously considered for all patients.
2. Some hearing aids fix the frequency where the input changes from omnidirectional to directional, but there are others available that set this frequency based on the configuration of the hearing loss, and/or this point also can be adjusted by the dispenser. In general, if the average of a hearing aid user’s thresholds at 250 and 500 Hz is less than 40 dB, the frequency where the input changes from omnidirectional to directional is set higher. This reduces the bass-boost induced low frequency noise the user may have experienced with traditional directional processing. Conversely, if their average thresholds at 250 and 500 Hz are greater than 40 dB, the frequency is set lower, as low frequency noise is less audible to this user.

Step 5: Manual and Automatic Beam Width Adjustments

Another development along this evolutionary journey is directionality where the front beam can be narrowed or widened depending on the signal level to the front. Specifically, the hearing aid monitors the relative levels of the sounds entering the front and rear microphone and automatically adjusts the width of the directional beam. The stronger the signal coming from the front, the more narrow the beam width is adjusted (Figure 4). As the level at the front microphone decreases, the beam width is widened. This also can be adjusted manually in some instruments fitting software where the beam width can be set to a wider or narrower setting.

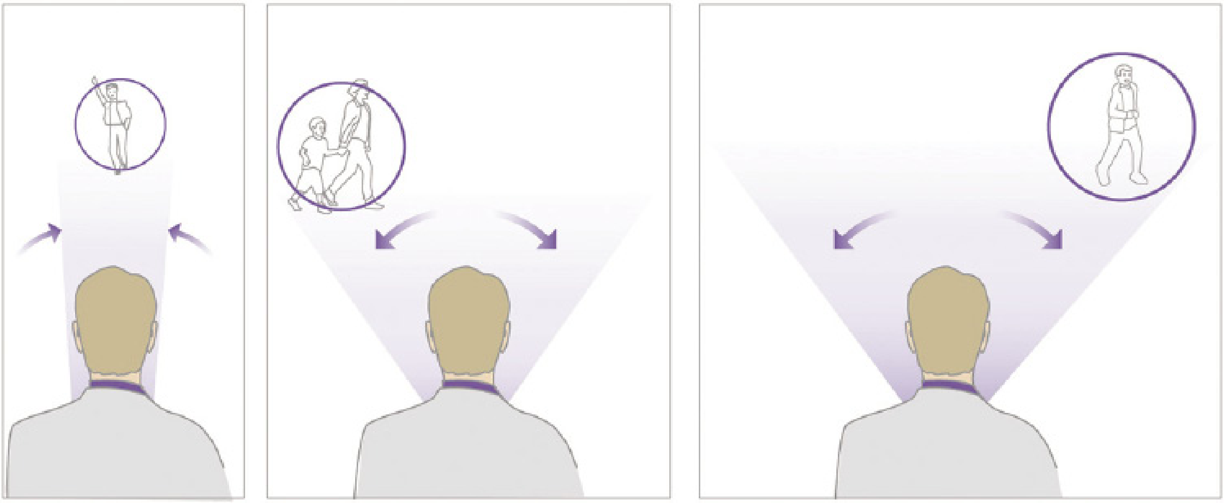


Figure 4. Examples of three settings of a hearing aid with adjustable directional beam widths. From left to right shows Narrow, Medium, and Wide correspond to listening scopes of approximately 50°, 70°, and 90° degrees, respectively.

Clinical Advice

1. Changing the beam widths has the effect of zooming in on a single talker located in front of the hearing aid user. This can be useful when the signal of interest is directly in front of the listener. Since a hearing aid cannot know where the hearing aid user’s signal of interest is located, these narrow beam width settings are best controlled by the user. That is, a separate memory in the hearing aid can be equipped with a narrow beam and the user can be counseled when to use this setting.

Step 6: Manual and Automatic Steering of Directional Pattern

Another development in directionality is the steering of the pattern of the directional response so that it is no longer forward facing. Steering of directionality is the ability of the directional system to move the area of most sensitivity to a location other than the front of the listener. The signal of interest is not always at the listener's front. Consider the often-cited situation where the driver of a car might want to hear the passengers in the backseat or the passenger seat. It is unsafe for drivers to turn their heads toward these speakers.

Some switching systems give the user control over where to steer the microphone making it most sensitive to the front, back, or the sides. Some devices automatically steer the directionality depending on the environmental input. This feature can be effective when used properly.[12]

Clinical Advice

1. A clinician should be extremely cautious when using this setting in the automatic mode, as the hearing aid will steer the pattern to the loudness modulated signal. This is not always the signal listeners want to hear in their environment. In the automatic mode, the hearing aid is making the decisions and the listener has to live with these settings.
2. If a user is motivated to use the setting manually and can understand when the steering should be activated, manual steering can be effective.

Step 7: Asymmetric Directionality

As stated earlier, directional microphones that were introduced in the early 2000s could be switched from omnidirectional to directional settings manually by the hearing aid user. In 2004, Cord et al[7] showed that many users (30%) did not switch between the settings. The study stated that users often did not know when to switch and/or did not want to do this manual switching in everyday life.

To overcome this manual switching problem, automatic switching hearing aids were introduced where the hearing aid automatically changes from an omnidirectional setting to a directional setting depending on the environment. These types of switching algorithms depend on environmental classification systems, which analyze the acoustic scene and make a decision about which microphone mode is most beneficial.

Thus, these systems are limited by the accuracy of the classification system and have no ability to determine the hearing aid user's intent in complex listening situations. One field trial of automatic switching systems (A. Dittberner, personal communication), showed that the switching systems were in the directional settings from 5% to 17% of the time. The results of Walden[6] suggest that the average user is in an environment in which a directional-microphone setting can be beneficial approximately 33% of the time. Thus, the switching algorithms currently used in hearing aids can be too conservative, with the end result being that the user is not in the directional setting when it could be beneficial. Additionally, the Cord et al7 study showed that, although many patients do not use their manual switching option, those who do use the option prefer the manual mode over relying on the decisions of automatic switching algorithms. The reason for this might be that the automatic switching algorithms are not switching effectively and/or appropriately.

Asymmetric Directional Fittings

The standard way to use directional processing in a bilateral hearing aid fitting has been to apply directionality simultaneously in both hearing aids of a binaural fitting. In other words, both hearing aids are in the directional setting in a noisy environment. Another way to use directional processing is to keep one hearing aid set to omnidirectional and the other hearing aid set to directional. This seemingly unconventional way to apply directional processing can provide a better listening experience for users of hearing aids and overcome the limitations of directional systems discussed above.

Specifically, an asymmetric fitting can overcome the lack of use of manual systems and the reliance on environmental classification systems. An additional benefit is that it does not cut a listener off from their environment as wearing two hearing aids in directional settings can do. The user can choose to attend to whatever signal they may be interested in hearing.

The key to asymmetrical directionality is to understand that one hearing aid in the directional setting and one in the omnidirectional setting provides the same SNR benefit as using two hearing aids set in the directional settings. Several studies have verified this, including Bentler et al,[13] Cord et al,[14] and Mackenzie and Lutman.[15]

Using hearing aids set asymmetrically comes with the added benefit of maintaining maximum auditory awareness for sounds arising from any direction. It was noted earlier that Walden et al6 determined directional microphones work the best when the signal of interest is close to and in front of the listener and the noise is spatially separated from the signal of interest. In the real world, there are many environments where these conditions are not true for a noisy environment. In fact, the signal of interest in real life is not always in front of the listener; it can be at any location. There also can be multiple signals of interest in an environment. For example, when a hearing aid user is sitting around a table with many speakers, the directional microphone settings might cut a listener off from what they want to hear. If a listener is using two hearing aids set to directional settings, he/she can be cut off from their environment making it difficult to even be aware of sounds from other directions.

Figure 5 is an example of a hearing aid user (seated woman) at a dinner table with many people. There are two speakers in this example: one behind the listener (the lady serving bread) and the man at the head of the table. A hearing aid cannot determine which of these speakers the hearing aid user would like to listen to. However, an asymmetric hearing aid fitting can allow the listener to choose. In an asymmetric directional setting, she can hear the man and receive the SNR benefit when she looks at him due to the directional microphone. She also can hear the woman behind her due to the omnidirectional microphone. She can then turn her head and attend to other conversations as desired.

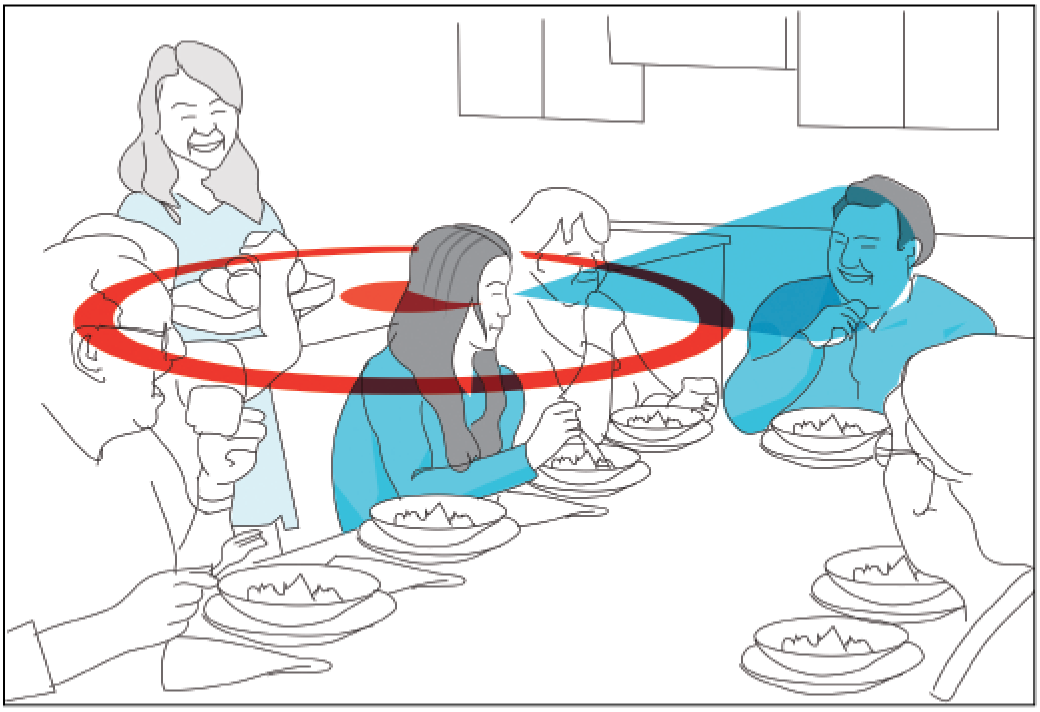


Figure 5. An environment showing the utility of an asymmetric hearing aid setting.

The hearing aid user (seated woman) can hear the speaker behind her due to the omnidirectional hearing aid and can follow the conversation with the man at the end of the table by simply looking at him due to the directional hearing aid.

In a traditional binaural directional setting, the hearing aid user would be completely cut off from the conversation happening behind her. In these traditional settings, users may report a feeling analogous to tunnel vision. That is, they are cut off from their surroundings. Asymmetric fittings give the hearing-impaired listener an experience more like that of normal-hearing listeners.

Finally, Cord et al[14] found improved ease of listening for asymmetric directional fittings as compared to bilateral directional fittings. Users do not feel as isolated from sounds originating from the sides and rear due to the environmental sound cues from the omnidirectional processing that is always available to them.

Clinical Advice

1. An asymmetric fitting gives the benefit of improving SNR without cutting the listener off from the environment.
2. Setting two hearing aids asymmetrically without a specific manufacturer setting might give the listener the annoying feeling of being unbalanced. Algorithms specifically designed for asymmetric listening use band-split directionality for a more balanced listening experience.

Step 8: Arrays to Narrow the Beam-width Further

Wireless communication between hearing aids has allowed for the implementation of another approach to directionality that uses an array of microphones. In this approach, the two microphones on one hearing aid are linked to the two microphones on the other hearing aid. This allows the null points of the beam to be moved further to the front, and a narrower beam (approximately 45°) to be created by the array. Traditional dual microphone systems are limited to a beam to the front within an angle of about 60°. A narrower beam then provides the potential for a more favorable SNR.

The narrow beam described here, however, is limited to situations where a listener wants to focus on one speaker located in front of them in a diffuse noise environment. The implementation of this feature in current technology requires the user to switch to a separate program to use the narrow beam. As described above in the section on asymmetric fittings, the disadvantage of such a system is being cut off from all other signals coming from other directions.

A research study comparing a narrow beam (about 45°) created by a microphone array versus a more traditional beam (about 60°) resulted in approximately a 1 dB SNR improvement in a laboratory condition. This specific condition utilized a diffuse noise environment with speech-shaped noise at 45°, 90°, 135°, and 180°. In another condition tested, a diffuse noise environment with continuous babble and ICRA4 noise from 60° and 90°, as well as babble noise from 135° and 180°, showed no difference in performance between the two conditions. These results emphasize the *specific environment* in which this feature could be useful.

Clinical Advice

1. Narrower beams should be only controlled by the user in a specific memory. These settings can be beneficial; however, they also cut listeners off from most of their environment, so they should be used only when the signal of interest is in front and the rest of the environment is not important to the listener.

Step 9: Outside the Hearing Aid

Greater directivity can be achieved using multiple microphones combined in arrays or second order

directionality. Arrays have greater directivity indexes providing greater SNR improvements; however, the arrays that have been available have not had widespread use due mainly to cosmetics. Even arrays of microphones on the frame of glasses are not desirable to hearing aid users.
What is becoming more widespread in use are small microphones that can be given to speakers and streamed wirelessly into the hearing aids. These microphones are often called companion microphones.

While typically not a directional microphone, companion microphones can dramatically increase the ability to hear from a specific direction. Early systems used a microphone on a wire plugged directly into a hearing aid. More commonly, FM systems have provided this benefit with fewer wires and, over the years, significantly reduced hardware requirements. SNR improvements with FM systems can be on the order of 15 to 18 dB depending on the listening environment.

However, these devices have been most commonly used for children in the classroom and are not widely used by adults—even though personal FM systems that can be used with hearing aids have been on the market for many years. The cost of these systems may be one reason that they are not commonly used.

Wireless connectivity in hearing aids has great potential to provide listeners with solutions that provide SNR improvement comparable to FM while being cosmetically and economically acceptable. This type of accessory is beneficial in many environments such as restaurants, meetings, lectures, cars, etc.

In the future, expect more of these microphones to be introduced. Companion microphones can be given to a speaker in a difficult listening situation and the speaker's voice will be picked up and sent wirelessly to the hearing aids. These types of microphones have ranges well beyond the range of directional microphones in hearing aids and bring the ability to hear in noisy situations to more users than ever before possible. Future developments will make these microphones available for more than one speaker so that a hearing aid user can listen to multiple speakers in a noisy environment.

Clinical Advice

1. Microphones that stream a voice wirelessly to a user's hearing aids benefit all patients with hearing loss when the environment has a poor SNR. Listeners with SNR losses greater than 8 dB will get more benefit from these companion microphones than with hearing aids with directionality.
2. SNR losses should be used to determine who is the best candidate for these types of devices. They should be widely recommended for and used by patients with higher SNR losses.

Summary

Over the last several years, developments in directional technology have improved listening in noise for hearing aid wearers. These developments have resulted in better sound quality, a more natural listening experience, and even better directionality than what was available when digital directional microphones were introduced in the early 2000s.

It isn't enough to fit hearing aids with directionality. A clinician needs to understand the benefits and limitations of the many settings available today. Appropriate programming and counseling will position the hearing aid user for the best possible listening experience in noise.

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