Tutorial on microphone technologies for directional hearing aids

By Stephen C. Thompson

Directional microphones have been available for use in hearing aids since the early 1970s. The clinical benefit of improved hearing in noise with a directional microphone has been understood since at least the 1980s. Nonetheless, hearing aids with directional microphone responses did not gain significant market acceptance until the mid-1990s. Why is that?

Part of the reason, certainly, is improvement in the design and directional performance in the more recent systems. However, directionality also has disadvantages in some listening situations. Modern directional systems all provide a method of switching between a directional mode and a non-directional mode so that the wearer can easily put the hearing aid in the appropriate mode for each listening situation. Many researchers believe that the primary reason for the wide acceptance of modern directional systems is this flexibility.

This article explains the different technologies that can be used to create directional microphone patterns. Regardless of the exact technology, all directional microphone patterns have the same major benefits and the same limitations.

Directional hearing aids, the subject of this special issue of *The Hearing Journal*, all include two or more microphones. All have both a non-directional mode of operation and one or more directional modes of operation. They all contain at least one omnidirectional microphone for use in those environments where it is needed. The second microphone may be either a two-port directional microphone or another omnidirectional microphone. When two omnidirectional microphones are used, their electrical outputs are combined to provide the directional pattern. In either case, sound from two acoustic ports is used to provide a directional response for the hearing aid.

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Of course, it is not strictly correct to call *any* mode of hearing aid operation a non-directional mode, because, in operation, a head-worn hearing aid always has some directionality from the user's head in addition to whatever additional directionality is provided by the microphone(s). To be strictly correct and speak only of the directionality that originates from the microphone, we should speak of the *free field* directional behavior of the system. The *free field* behavior of a hearing aid is the behavior of the device when it is measured by itself, not on a head, and not placed near any other large object that could affect the sound field. Figure 1 shows several of the free field directional patterns that are possible.

The directional behavior of the hearing aid can result from two different designs of the microphones. In the first design, a two-port directional microphone, the directionality comes entirely from the microphone. This type of microphone has been available for use in hearing aids since at least 1971. The design of the directional microphone can be adjusted by the microphone manufacturer to provide a range of directional patterns, examples of which are shown in Figure 1.

In a hearing aid, the microphone then provides a single fixed directional pattern. In order to provide the capability to switch to a non-directional mode of operation, a second microphone, one with an omnidirectional free field pattern, must also be included in the aid. This method of using both a directional and an omnidirectional microphone can be called a "directional with omni" system.

The second way to provide a directional response in a hearing aid is to use two omnidirectional microphones, and to combine their electrical output signals to provide a directional pattern. Methods to do this are discussed later. Clearly, such a system can provide an omnidirectional free field pattern by simply using either one of the two microphones alone. This type of system can also provide multiple, selectable directional patterns by changing the way the signals are combined to form the pattern.

To better understand the operation of directional microphones, it is necessary first to understand the operation of the standard, non-directional microphone.

THE OMNIDIRECTIONAL MICROPHONE

A diagram of an omnidirectional hearing aid microphone of a type manufactured by Knowles Electronics is shown in Figure 2. The microphone is basically a closed box that is divided into two small volumes by a thin polymer diaphragm.

Sound pressure enters the microphone through a small tube shown at the left, and then travels to the region called the "front volume" of the microphone. In the front vol-

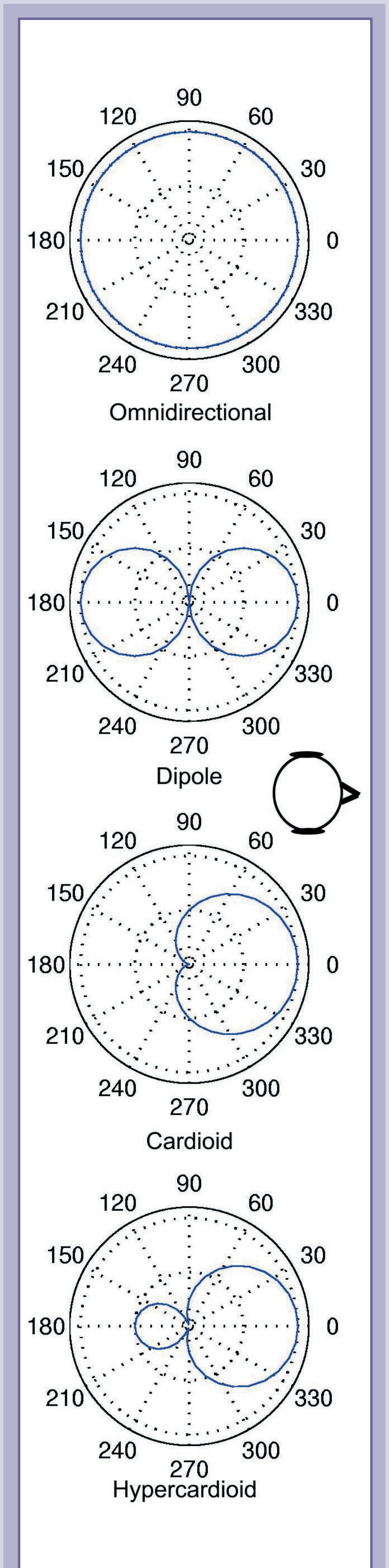

Figure 1. *Free field directional responses that are possible with directional microphones or dual-microphone processing.*

ume, the sound pressure creates a small motion of the diaphragm. On the other side of the diaphragm, the "back volume" contains a metal plate that is coated with an electret material that holds a permanent electrical charge. The motion of the diaphragm near the charged back plate creates a small electrical signal that is amplified to become the electrical output signal of the microphone.

THE DIRECTIONAL MICROPHONE

The directional microphone is very similar to the omnidirectional microphone described above except that it has a second sound entry port. In use, the two ports are normally aligned horizontally, along a line that points in the direction the user is facing. Thus, one port is called the "front port" and the other the "rear port" or "back port."

As Figure 3 shows, the front port brings sound into the front volume of the microphone and the back port brings sound into the back volume. This rear port often contains a screen resistance, whose purpose will be discussed below. Since both sides of the diaphragm now have an acoustic pressure, the diaphragm motion is driven by the *difference* in acoustic pressure between the front and back volumes. Consequently, a directional microphone of this type is often called a pressure-difference microphone or a pressure-gradient microphone.

If the acoustic pressure in the front and back volumes were the same, then the pressure difference would be zero and the microphone would have no output. Luckily, this does not occur because of the separation between the two sound entry ports. This means that for sounds that originate in front of the user the sound arrives at the front port a little sooner than it arrives at the back port. This time delay causes a small phase shift between the pressure signals in the front and back volumes.

As Figure 3 illustrates, the time delay and phase shift vary for different arrival angles of sound. For each different arrival angle, there is a different time delay and a different output for the microphone. The small pattern at the center of Figure 3 shows the case where no damping screen is used in the microphone. Sounds coming directly from the side have no time delay, and therefore the microphone has no output in this direction. When a damping screen is used, its resistance value can be selected to give any of the free field patterns shown in Figure 1.

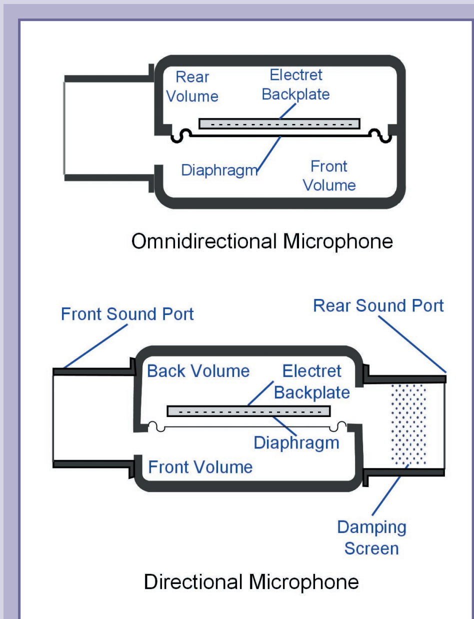

Figure 2. *In a simple microphone, sound pressure enters the front volume and causes a small vibration of the diaphragm. The directional microphone has two ports. The diaphragm is driven by the pressure difference in the front and back volumes.*

The subtraction process that takes place in the difference microphone generally causes the microphone sensitivity to be significantly lower than that of an equivalent omnidirectional microphone. Figure 4 shows the frequency response of the sensitivity of a directional microphone and of a similar omnidirectional microphone. The decrease in sensitivity is significant, especially at low frequencies, and is greater when the separation of the two ports is smaller.

DUAL-MICROPHONE PROCESSING

The other approach to achieving a directional pattern in a hearing aid is to use two omnidirectional microphones and combine their outputs to create the directional signal. Figure 5 shows the general form of the processing that is needed to produce a directional pattern. The output signal of one microphone is subtracted from that of the other. The specific directional pattern may be changed among the possibilities shown in Figure 1 by adding a simple delay circuit, as shown in Figure 5. The electrical processing can be done in either analog or digital circuitry within the hearing aid.

The two methods of obtaining directionality have much in common. Figure 6 shows functional block diagrams of the two methods. In the two-port directional microphone, the acoustic signals from the two ports subtract by driving the diaphragm on its opposite sides. The difference signal is then converted to an electrical signal by the microphone. In the dual-microphone directional system, the acoustic signals at the two microphone ports are each converted to electrical signals and then subtracted in the electrical circuits.

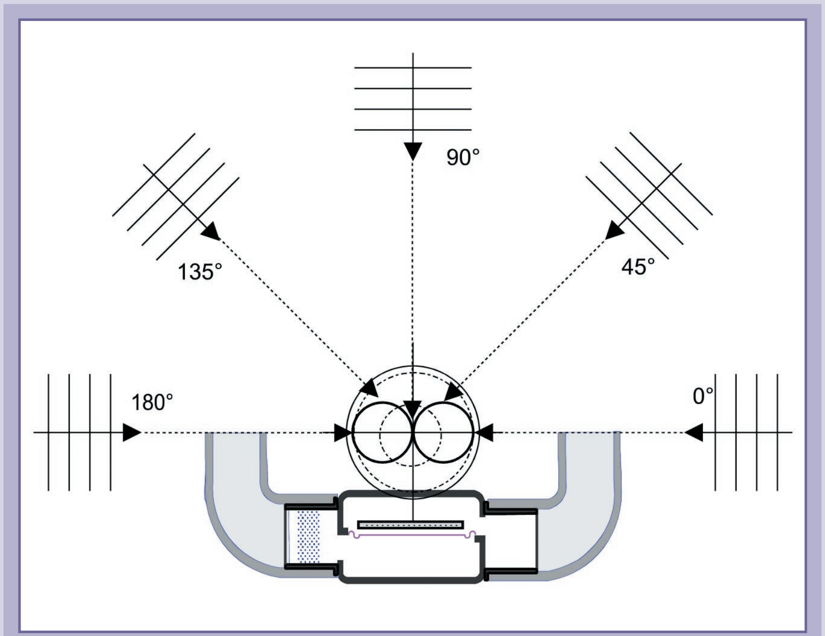

Figure 3. *Sound from different directions arrives at the two ports with different time delays and generates different microphone responses.*

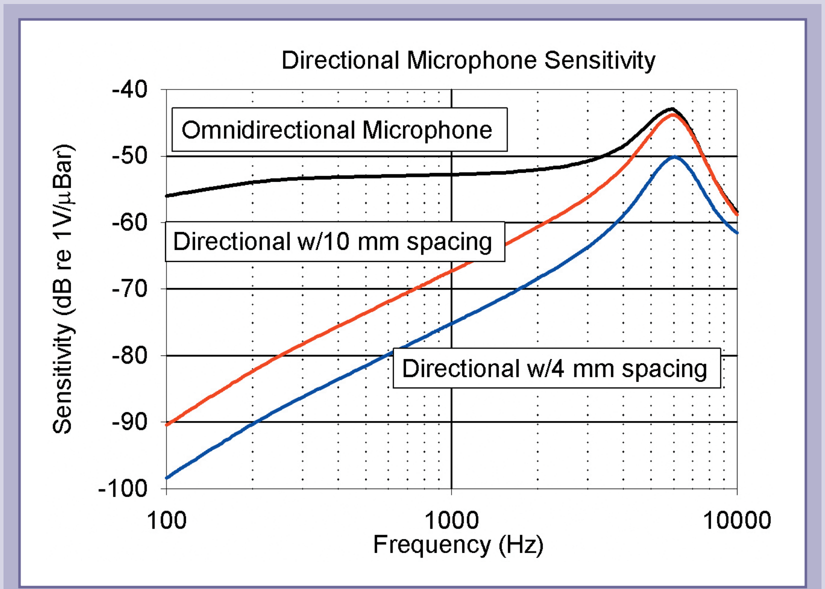

Figure 4. *The frequency response for a directional microphone, or for two microphones processed to give directivity, falls at low frequency.*

In each system, the specific pattern shape (one of the options shown in Figure 1) is controlled by a a component in the design of the system. For the two-port directional microphone, it is the damping screen in one of the microphone ports that forms part of an acoustic filter to set the pattern. In the dual-microphone system, the pattern is set by the characteristics of an electrical filter.

The functional similarity of the two methods means they are also alike in many aspects of their performance. For example, the frequency response curves of Figure 4 apply to both designs. The comments on internal noise and on wind noise later in this article also apply equally to both designs.

One way in which the systems differ is that the pattern of the two-port directional microphone is set by the microphone manufacturer through the selection of the damping resistor at the time of manufacture. In the dual-microphone system, it is possible to change the characteristics of the electrical filter under control of the DSP to obtain different directional patterns in different situations. Thus, a hearing aid can provide a number of patterns that can be selected under manual or program control, or it can provide an adaptive directional system that continually modifies the pattern with the objective of maximizing the SNR in a changing environment.

MICROPHONE MATCHING

One important consideration in the design of a hearing aid with two omnidirectional microphones is unique to that design. When there are two microphones, their inherent sensitivities must be well matched for the patterns to have their intended shapes. Significant microphone mismatch can degrade the patterns in unintended ways.

Hearing aid manufacturers can do several things to ensure that the microphones are well matched. First, they can purchase microphones in matched pairs from the microphone component supplier. To do this, the microphone manufacturer must measure the sensitivity of all microphones and select the units of a matched pair to have sensitivities that match within a specified tolerance.

A second approach to sensitivity matching is to compensate for the differences that remain by adjusting the gain of the amplifier for one microphone relative to the other. Hearing aid manufacturers commonly do this as a final step in the assembly of a hearing aid.

A final possibility, called "dynamic matching," is performed in some DSP aids. Using dynamic matching, the processor constantly examines and compares the relative sensitivity of the two microphones. If they are perfectly matched, the signals from the two microphones should have the same overall level and frequency response. Any differences in level or response can, in principle, be corrected by changing the gain and frequency response of the processing for one of the microphones. While no such process can function perfectly, the various forms of dynamic matching may provide an important improvement in matching over the life of the aid.

Of course, it is essential that the microphones maintain their match throughout the life of the hearing aid. Since the first dual-microphone hearing aids were introduced, there has been an underlying concern that a relative "drift" in the sensitivity of the microphones could degrade the instrument's directional performance.

Perhaps the most significant source of performance drift in the field is partial or complete clogging of the microphone ports with debris. It seems inevitable that significant port clogging will affect the patterns. Anecdotal evidence from hearing aid manufacturers does not indicate a significant problem with directional performance drift in microphones that are not clogged or otherwise obviously defective. However, further studies are warranted.

DISADVANTAGES OF DIRECTIONALITY

Internal noise

To this point, we have not mentioned any *disadvantages* of directional patterns in hearing aids. However, there are two undesirable features of directional patterns, which in certain circumstances make it best to switch the hearing aid to an omnidirectional mode.

One disadvantage is internal noise from the hearing aid. In a quiet environment, internal noise may be noticeable. Several studies have shown that the low level of internal noise that is inevitably generated in the microphone and amplifier circuits is not normally audible to the hearing-impaired user.[1,2] However, these studies have assumed that an omnidirectional microphone is used in the aid.

When a directional microphone or a

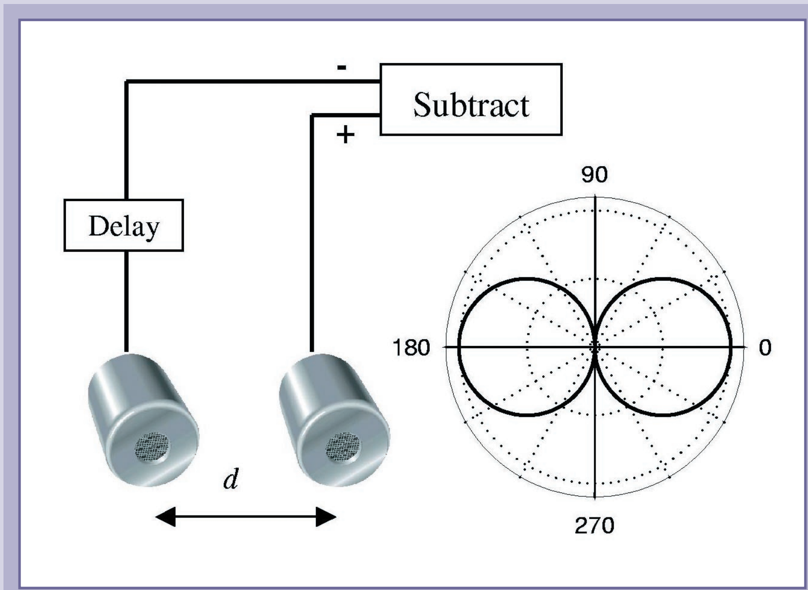

Figure 5. *A directional pattern is generated by two omnidirectional microphones whose outputs are subtracted.*

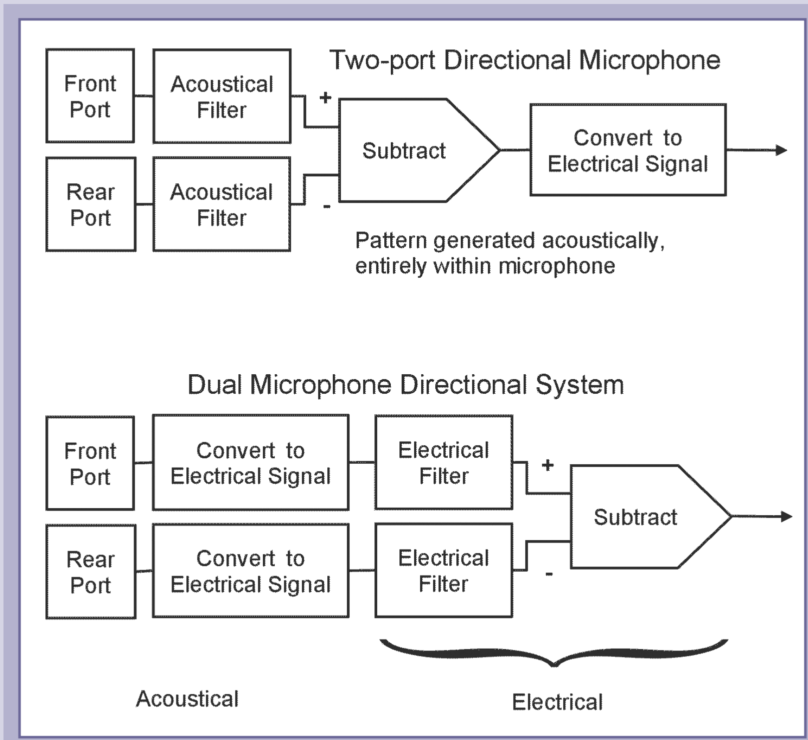

Figure 6. *The two ways of obtaining directionality do the same things in a slightly different order. The two-port directional microphone does it all in the acoustics of the microphone. The dual-microphone system does the same things electrically.*

pair of matched microphones is used to form a directional pattern, the sensitivity falls (see Figure 4). The sensitivity affects the level of the sensed signal, but the internal noise level is approximately the same as that of an omnidirectional microphone. Consequently, the signal-to-noise ratio (SNR) at low frequencies is significantly lower in a directional pattern.

A hearing aid that uses low-frequency amplification to enhance the audibility of low-frequency signals will naturally amplify the low-frequency internal noise as well. Figure 4 indicates that perhaps 20 dB of additional amplification is needed in a directional pattern to achieve the same level of audibility as in an omnidirectional microphone. This amount of amplification is quite likely to raise the level of internal noise above the environmental ambient noise in a quiet environment. Thus, the omnidirectional pattern is more appropriate in quiet.

In a noisy environment where the benefits of the directionality are needed, the internal noise of even the directional pattern will be well below the ambient level. In hearing aids that allow the user to control the directional mode manually, the user must be counseled that the directional mode should generally *not* be used in quiet situations. Some hearing aids provide for automatic switching from the omnidirectional to the directional-mode in backgrounds where the noise level exceeds a manufacturer-determined threshold.

Wind noise

The presence of wind noise can create another situation in which directional microphone patterns seem noisier than omnidirectional patterns. In this case, the noise is not generated by the microphone, but originates in the turbulent air flow as wind moves past the head and shoulders. We all hear wind noise in even a moderate breeze, and it can be quite loud in many situations.

An explanation of wind noise is presented in the box on this page. The important feature is that the noise is mostly generated within 10 cm of the ear.[3]

This wind noise presents two difficulties for hearing aid users. First, the microphone is located very close to the source of the noise, while for normal hearers the eardrum is farther from the source and shielded somewhat from it at the end of the ear canal. This affects the signal level of all microphones, whether or not they are directional.

Secondly, directional patterns are relatively more sensitive to sounds from the near field than to sounds from farther away. This is why wind noise is received at a much higher level in directional microphone patterns than in omnidirectional patterns. Also, note that the wind noise effect is the same in a dual-microphone directional implementation as in a two-port directional microphone.

For the directional hearing aid user, this means that the aids should be switched to the non-directional mode in wind noise.

SECOND-ORDER DIRECTIVITY

The directional patterns described so far are all in a category called "first-order difference patterns." One method of further improving the SNR in a noisy environment beyond the level that can be achieved

WIND NOISE: WHAT IT IS AND WHY IT'S A PROBLEM

The term "wind noise" is used to describe several different ways that wind can generate sound. For example, wind can cause a loose shutter to bang against a house or it can cause a flag to rustle and snap. In these cases, the wind has caused an object to move, and the motion makes a sound.

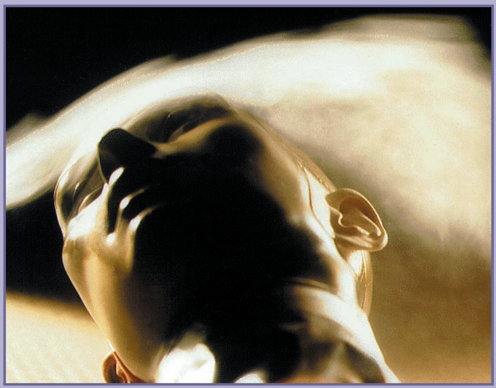

Figure 1A. *KEMAR head in a wind tunnel, with wind from the right. Wind is initially very smooth and quiet. After passing the head there is considerable turbulence and noise that originates close to the head.*
(Photo courtesy National Acoustic Laboratories.)

In other cases, wind moving past an object can create a howling sound, even though the object does not vibrate. Here, the sound is caused by turbulence that is created in the moving air as it passes by the object. This turbulence, which cannot be seen, is very similar to the turbulence in a fast-moving stream as the water flows around and over large rocks. We have all experienced this kind of wind noise while inside a house during a windstorm. The sound of the howling wind originates in the turbulence of air motion past the walls and roof.

The form of wind noise that most interferes with our ability to hear and communicate is the noise generated by air flow around our own head. Here the sound is generated within centimeters of our ears, and may be heard at quite a high level because of this close proximity.

Studies of this phenomenon have been performed by researchers at the National Acoustics Laboratories (NAL) near Sydney, Australia.[3] Figure 1A shows a photo of KEMAR in the NAL wind tunnel. A thin layer of smoke in the wind shows the character of the air flow as the wind moves from left to right in the figure.

Before it encounters the head, the wind is moving smoothly, and the smoke streams in a straight line. After passing KEMAR, the smoke spreads out considerably following the swirls and eddies in the turbulent air flow. For different angles of wind incidence, turbulence may be generated by the pinna and be even closer to the ear.

Turbulent generation of noise very close to the ears can have a major impact on the ability to understand sounds from more distant sources. This is true for people with normal hearing as well as for hearing aid wearers. However, wind noise may be more problematic for people wearing hearing aids, because the microphone is closer to the wind noise source and is not as effectively shielded as the eardrum at the end of the ear canal. The noise source close to the head is especially problematic for directional hearing aids because the directional patterns are relatively more sensitive to sounds from the near field than from farther away. An omnidirectional microphone pattern has much better SNR in wind noise situations.

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