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Design Considerations in Directional Microphones

A perspective on the trade-offs inherent in designing directional hearing systems

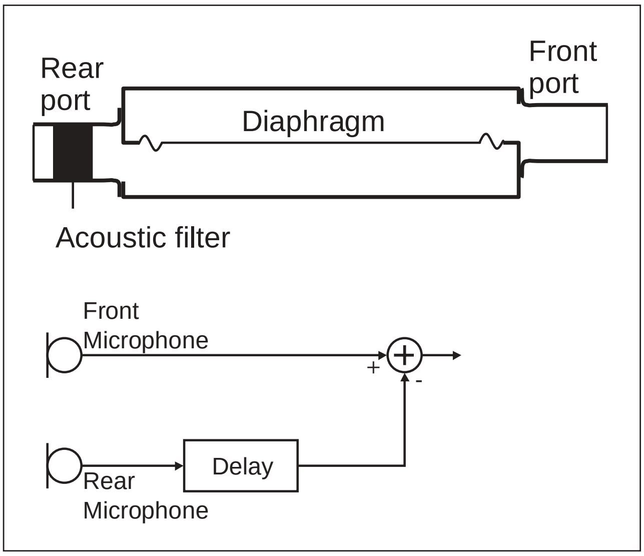
Directional microphones have been used effectively as early as the 1970s as a means to improve speech understanding in noisy surroundings.[1, 2] In recent years, there is renewed interest in applying this technology to further enhance the performance of hearing instruments in noise. Valente[3] provided an excellent tutorial that differentiated the types of microphone technology and summarized the clinical studies that addressed their relative efficacy. What remains less understood are the considerations in choosing a particular design for a directional microphone, and how these choices affect the real-world use of the directional hearing instrument. Several of these factors are addressed below.

Design Differences

There are two principal ways in which today's directional hearing instruments achieve their directional characteristics: a dedicated directional microphone using a single microphone cartridge with two sound inlets (referred to as dedicated directional microphone henceforth) and multiple microphones using two omnidirectional microphones as sound inlets (referred to as dual-microphone henceforth).

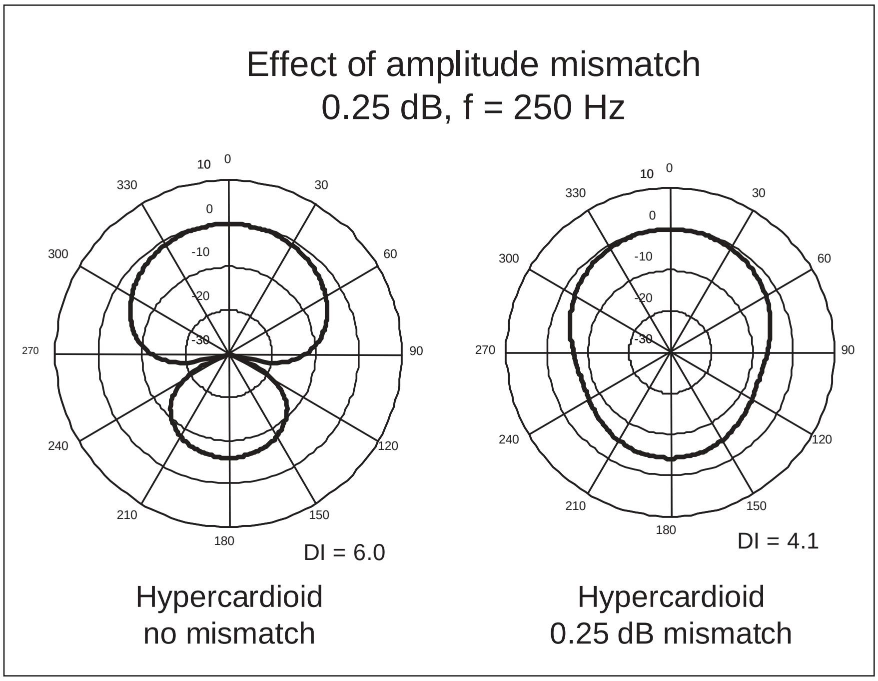
Figs. 1a-b show the schematic diagrams of these two types of microphones. Fig. 1a shows a dedicated directional microphone with the single microphone separated by a membrane and two inlets. Sound enters the cartridge via the front port and the rear port. The signal arriving at the front port will be correlated with the signal arriving at the rear port, and the net output of the microphone is determined by the pressure difference across the membrane. By adjusting the magnitude of the damping material in the rear port (at a fixed distance between the microphone ports), one can delay the signal entering through it and create different directional patterns. Note that the signal processing that creates the directivity is done before the acoustic signal is converted into an electrical signal. This could limit the amount of signal processing to the electrical signal. An example of the use of this type of directional system is the SENSO C9/C19 hearing instrument. Similarly, the directional microphone in Etymotic Research's D-Mic also uses a single cartridge design to achieve its directional properties.

Fig. 1b shows a directional microphone system comprised of two omnidirectional microphones. The acoustic signals are converted first into an electrical form before any signal processing takes place. Because the signals entering the two microphones are correlated, the



Figs. 1a-b. Schematics of a) a dedicated directional microphone with the single microphone with two inlets separated by a membrane (adapted from Knowles Electronics, Inc.); b) a directional microphone consisting of two separate cartridges, each containing one membrane and one acoustical input port.

output from the two microphones can be manipulated to yield the desired directional pattern. Typically, an electrical delay is applied to the electrical signal from the rear microphone. This allows the convenient use of different delays to achieve various polar patterns. It also allows switching between omnidirectional and directional modes of operation. Several high-end hearing instruments use the dual-microphone design to achieve different polar patterns and the ability to switch between modes. Digital signal processing techniques could potentially find more uses for a dual-microphone system in addition to these two functions.



Figs. 2a-b. Directivity pattern at 250 Hz of a directional unit consisting of two omni-directional microphones. Distance between the microphone inlets is 10 mm. a) The internal delay is adjusted to give a hypercardioid pattern with perfect amplitude and phase match. b) Amplitude mismatch of 0.25 dB between microphones.

Microphone Considerations

Microphone mismatch: A major consideration in the use of dual microphones to achieve the desired directional characteristics is to ensure that both microphones are identical in their sensitivity and phase characteristics at all times. Otherwise, deviations from the intended polar patterns would occur. Unfortunately, all electroacoustic transducers suffer from sensitivity drift over time as a result of aging, and excessive temperature and humidity may accelerate the drift. Additionally, significant variations may exist among microphones, and it is often impossible to predict how a microphone performs over time.

Amplitude mismatch: In a dual-microphone system, drifting of the individual microphone at different rates could result in different amplitude responses of the two microphones. Any amplitude mismatch could have a deleterious effect on the directivity, especially in the low frequencies. Figs. 2a-b show the difference between a) the intended directional characteristic, and b) the actual directional characteristic at 250 Hz when there is a 0.25 dB mismatch between the two microphones. Because the result of amplitude mismatch is symmetrical, the same polar pattern will result regardless of which microphone shows the lower sensitivity. Accelerated aging studies[4] (60^0C with 100% humidity over one month) conducted by Widex showed that the drift in amplitude sensitivity varies among individual microphones with a range around 0.8 dB in most frequencies. This is sufficient to eliminate most of the directivity in the low frequencies.

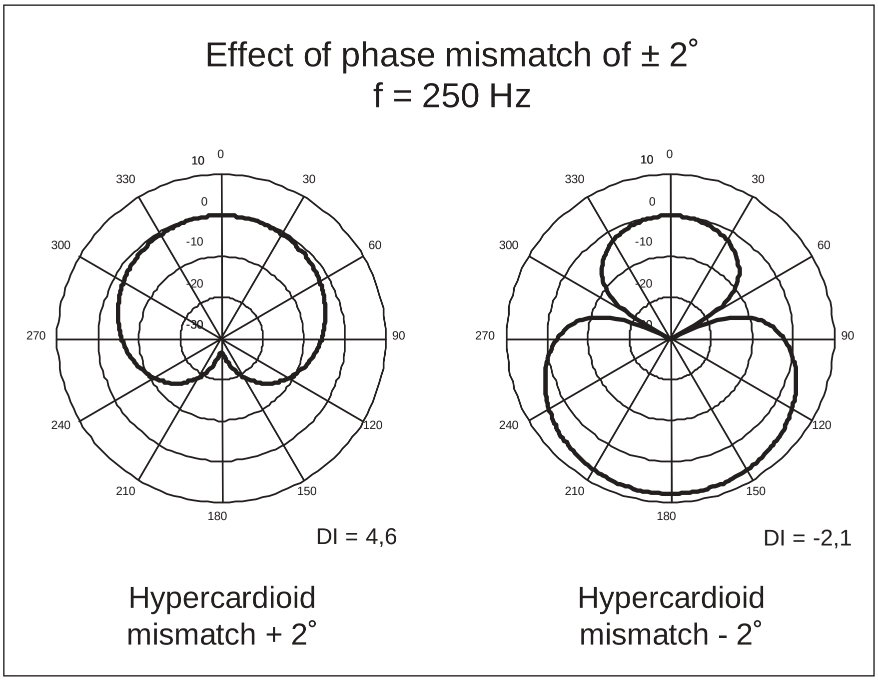
In a dedicated directional microphone, a possible drifting of the microphone sensitivity will not influence its directional characteristic. This is because the change in sensitivity will apply to the signal from both the front port and the rear port.

Phase mismatch: Another type of microphone mismatch that is commonly overlooked is phase mismatch. Figs. 3a-b show the polar pattern of a directional microphone that is supposed to have a hypercardioid pattern at 250 Hz. Instead, a cardioid pattern is seen when the phase of the front microphone is 2^0 less than the signal from the rear microphone (Fig. 3a). This yields a lower directivity index (DI) even though it still maintains a significant directional advantage. Fig. 3b shows the polar pattern with the same phase difference (2^0) but with opposite sign. A "reversed hypercardioid" pattern is seen along with a negative DI. This suggests that the microphone is more sensitive from the other directions than the front. Clearly, the effect of phase mismatch is asymmetric between microphones. Accelerated aging studies[4] indicate that phase drift also varies among individual microphones with the mode around 3^0. Furthermore, the occurrence of amplitude drift is independent from the occurrence of phase drift.

Performance Differences

The performance of directional microphones has been evaluated through measures of signal-to-noise ratio improvement and directivity index.

Signal-to-noise ratio (SNR) improvement: Because a directional microphone is based on the principle of subtraction of correlated inputs, both the dedicated microphone approach and the dual-microphone approach should yield similar performance advantages.



Figs. 3a-b. Directivity pattern at 250 Hz of a hypercardioid microphone with perfect amplitude match (same as Fig. 2a), except a) phase mismatch of 2^0 (front microphone is delayed); b) phase mismatch of -2^0 (rear microphone is delayed).

Indeed, this is the case with today's directional systems. Valente et al.[5] reported that a dedicated directional digital hearing instrument yielded an average SNR improvement of 7 dB compared to its omnidirectional version. This is similar to the 7.4 dB reported by Valente et al.[6] on a dual-microphone system. Kuk et al.[7] reported an average SNR improvement of 6.5 dB on the same dedicated directional hearing aids in children (compared to own aids), and Gravel et al.[8] reported that a dual-microphone system showed similar SNR improvement in children.

Ricketts & Dhar[9] compared the SNR advantage of three directional-hearing instrument systems: a digital dedicated directional instrument, a programmable dual-microphone instrument and a digital dual-microphone instrument. The SNR required by all three directional hearing aids to reach 50% correct identification on the HINT test was determined with noise presented from the sides and back. No significant difference was found among the three directional systems in both an anechoic chamber and a reverberant room where the evaluation was conducted.

Directivity index (DI): The three hearing instruments used in the Ricketts & Dhar[9] study differed in their directivity indices with the dedicated system showing the lowest (DI = 2.5 dB) and the dual-microphone programmable system the highest (DI = 4.1 dB). This brings up several interesting questions. First, will the use of a dedicated directional system always result in a lower DI? Secondly, which frequency component of the DI can one deduce from studies by Ricketts & Dhar[9], Valente et al.[6] and Gravel et al.[8] that has the most influence on the magnitude of the SNR enhancement?

The answer to the first question can be gleaned from the design principle of a directional microphone. Because the resulting polar pattern of a directional system is simply an interaction of the separation between microphone inlets and the delay used in the rear microphone, there should be no difference in the theoretical outcome. In other words, both directional systems have the same potential to reach the same directivity index. The difference in DI seen among directional systems is a matter of design choice and not a limitation of the number of microphones used in the design. A good example to show that a dedicated directional system can have a high DI is the D-Mic, a dedicated directional microphone which has a DI of 3.3 dB at 1000 Hz and a DI of 6.3 dB at 4000 Hz.

A conclusion from the Ricketts & Dhar study[9] is that signal processing used in the hearing instruments can interact with the directional microphone to yield the desired SNR improvement. Because all three directional hearing instrument systems have a moderate DI in the low frequencies but differing DI in the high frequencies, another interpretation of the results is that the directivity index in the low frequencies is primarily responsible for the improvement in SNR in "real-life" environments.

Minimizing Internal Noise

One consequence of adding a signal (from the front microphone) with its delayed replicate (from the rear microphone) to achieve a directional advantage is that the sensitivity of the microphone at low frequencies is reduced also for sounds presented directly in front of the listener. For a given delay and distance between microphones (or inlets), the reduction in the low frequencies is at a rate of 6 dB per octave. This loss of sensitivity in the low frequencies can reduce the overall loudness of sounds, and may affect speech perception and sound quality.[10] While acceptable for some people with sloping hearing losses, this reduction in loudness would not be acceptable for those who require low frequency gain from the hearing aid. This includes people with a flat hearing loss and those who are more reliant on low frequency gain for speech intelligibility.[13]

Another consequence of the reduced sensitivity at the low frequency is that the input- related noise level, which is slightly biased towards the low frequency in omnidirectional microphones, will be further biased in the low frequency (Fig. 4). In order to restore the sensitivity of the directional microphone to that of the omnidirectional microphone, one has to electronically equalize the response by boosting gain in the low frequencies relative to the microphone output. This further raises the level of the circuit noise at the hearing aid output by an amount associated with that boost.

The increase in output noise from response equalization is present in both the dedicated microphone and dual-microphone directional systems. However, the level of noise is somewhat lower in the situation of the dedicated microphone because the extra opening behind the microphone membrane allows the membrane to move more freely compared to the omnidirectional microphone with a closed back-volume. [14]

The wearers of the equalized directional microphone may detect a relatively high noise level when comparing it to its omnidirectional mode. On the other hand, several real-life factors may reduce the perception of this additional noise by its wearers. First, this additional noise is only noticeable in the directional mode, which is optimal for use in noisy situations. Under such situations, the noise in the environment masks the internal noise and renders it inaudible. This is true even in relatively quiet environments where low frequency ambient noise predominates. Second, some hearing instruments allow wearers to switch between omnidirectional and directional microphone modes.

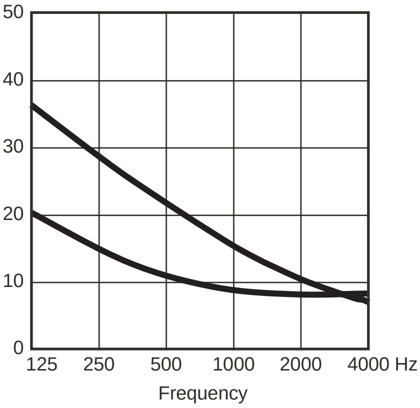


Fig. 4. Equivalent input noise in third octave bands of two similar hearing instruments, one with an omni-directional microphone (lower curve) and one with a directional microphone (upper curve).

Third, wearers with moderate-to-severe hearing losses in the low frequencies may not hear this noise. Fourth, people with mild-to-moderate losses in the low frequencies may not hear this noise because the relatively large vent in their hearing aids reduces the insertion gain at low frequencies. This also reduces the sensation level of the circuit noise. Such would not be possible if a small (or no) vent is used.

On the other hand, because modern nonlinear hearing instruments with a low compression threshold provide more gain for soft sounds than linear hearing instruments, their wearers may hear this internal noise more readily. Lowering of the gain for the soft input would be necessary.

Microphone Inlet Distance

The polar pattern of a directional microphone is formed by an interaction of the distance between the two microphone openings and the delay of the rear microphone input. Although different delay and distance combinations could yield the same polar pattern, the choice of the optimal distance between microphones is limited by more than the physical space available. For one thing, a shorter distance between microphones would reduce the sensitivity of the microphone, especially in the low frequencies. Fig. 5 shows that, as the distance between the microphones decreases, the sensitivity in most of the frequencies also decreases. As discussed in the previous section, providing extra gain can compensate for this loss in sensitivity, but a higher level of circuit noise can be the result.

Although a longer distance may be desirable for a lower internal noise, the directional properties may be compromised if the distance is too long. This effect is first seen in the high frequencies. Fig. 6 shows the polar patterns of an 8 kHz signal as the distance between microphones is increased from 5 mm to 25 mm. As the distance is increased from 5 mm to 12 mm, an increase in sensitivity in the frontal direction is seen. Accompanying this increase in sensitivity is a decrease in the DI (from 5.9 to 5.0). When the distance is further increased to 25 mm, the sensitivity of the microphone increases in *all* directions except the front. This results in a negative DI, signifying that the maximum sensitivity is not in the frontal direction.

It appears that a microphone distance of 5-12 mm is a good compromise between the desired di-

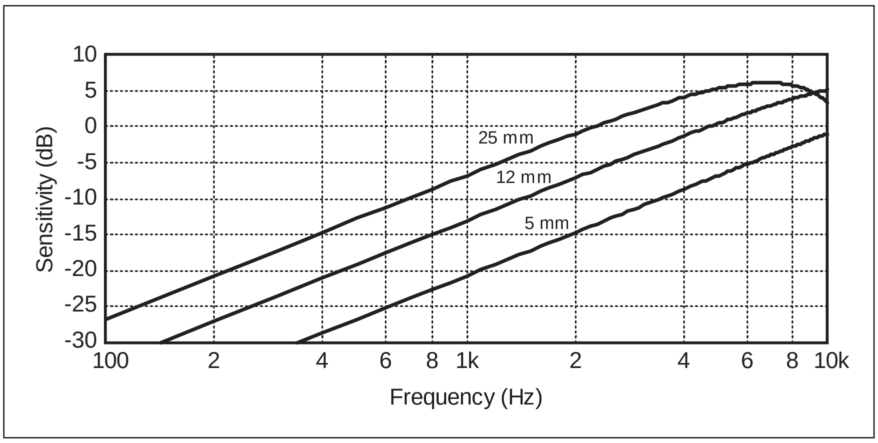


Fig. 5. Effect of port (or microphone) separation on sensitivity in a directional microphone.

Sounds Originating from the Sides and Back of Listeners

A directional microphone achieves its improvement in signal-to-noise ratio by reducing its sensitivity to sounds that originate from the sides and the back. The effectiveness of such an action is reflected in the magnitude of the directivity index. Indeed, the higher the directivity index, the less sensitive the microphone is to sounds from anywhere but the front.[8] In the classic situation where the noise source is from the sides and the back, a directional microphone has been shown to achieve the desired SNR enhancement.

On the other hand, if speech (or any desirable signal) originates from these directions, the use of a directional microphone could result in a loss of the desired audibility. This was demonstrated by Lee et al.[11] who compared the speech recognition scores between omnidirectional and directional microphones when speech was presented from the back of the wearers. At presentation levels of 50 dB SPL and 65 dB SPL in quiet, a decrease in speech recognition scores was observed in the directional mode compared to the omnidirectional mode. Indeed, at the soft speech level (i.e., 50 dB SPL), a decrease of over 20% in speech understanding was noted (omni = 37%; dir = 13%). This demonstrates the potential limitations of a directional microphone in situations where it is not designed to perform optimally. Under such situations, the wearer may miss important information that could result in miscommunication. Some mechanisms to compensate for the lost microphone sensitivity would be necessary.

An obvious solution to the problem is to provide a switch that allows the wearer to choose between an omnidirectional mode and a directional mode. Indeed, this is a feasible solution for individuals who physically and cognitively know when and how to switch between the two microphone modes. On the other hand, individuals who may not have the cognitive or the physical ability to use the switch cannot benefit from such a solution. Furthermore, one cannot expect those who are capable of switching to always switch at the opportune time. Some mechanisms to ensure proper use of the omnidirectional and directional modes would be critical, especially for directional microphones with a high DI.

Another solution that can partially compensate for the loss of sensitivity is to implement the directional microphone on a wide dynamic range compression (WDRC) circuit that uses a low compression threshold (CT). As Kuk[12] indicated, a low CT provides more gain to soft sounds than a comparable hearing instrument with a high CT. The extra gain could compensate partially for the reduction in sensitivity in the directional microphone.

This possibility was evaluated in the Lee et al.[11] study which reported on the speech scores obtained by a dedicated directional microphone with a low CT compared to the speech scores obtained with a dual-microphone system (utilizing a typical CT) in the directional and omnidirectional microphone modes. When soft speech was presented from the back, the dedicated directional microphone yielded an average speech score of 44%, whereas the dual microphone system yielded a speech score of 37% when it was in the omnidirectional mode and 13% when it was in the directional mode.

The higher score with the dedicated directional instrument suggests that the low-CT system is as effective as other hearing instruments with an omnidirectional microphone in picking up soft sounds from the back. Such will not be the observation if it were compared to the same hearing instrument with an omnidirectional microphone. The fact is that a directional microphone reduces sensitivity and a low CT minimizes its negative impact. Such a design (i.e., a low CT) would be beneficial in all hearing instruments with a directional microphone, regardless of the presence of an omni/directional switch.

rectivity and internal noise, and there is no difference between a dedicated and a dual-microphone system in this respect. The small separation between microphone ports makes it possible to have a directional microphone not only in BTEs and ITEs, but also ITCs. Although a directional microphone may even be possible for CICs, its use in these instruments may be more problematic because the recession of the hearing instrument into the ear canal would leave room for concha modification of the input signal and compromise the directionality of the system.

Minimizing Wind Noise

Wind noise is created when the flow of air particles is obstructed (e.g., by the head and pinna) and becomes turbulent. Vortices (eddies) are created around these obstacles. Wind noise increases as the wind velocity increases, and its level is also dependent on the direction of the wind relative to the orientation of the head.

Although wind noise is a problem for hearing aid wearers in general, wearers of directional microphones are more likely to comment that wind noise is bothersome and makes communication more difficult. Because the properties of wind noise are different from those of other noises, a di-

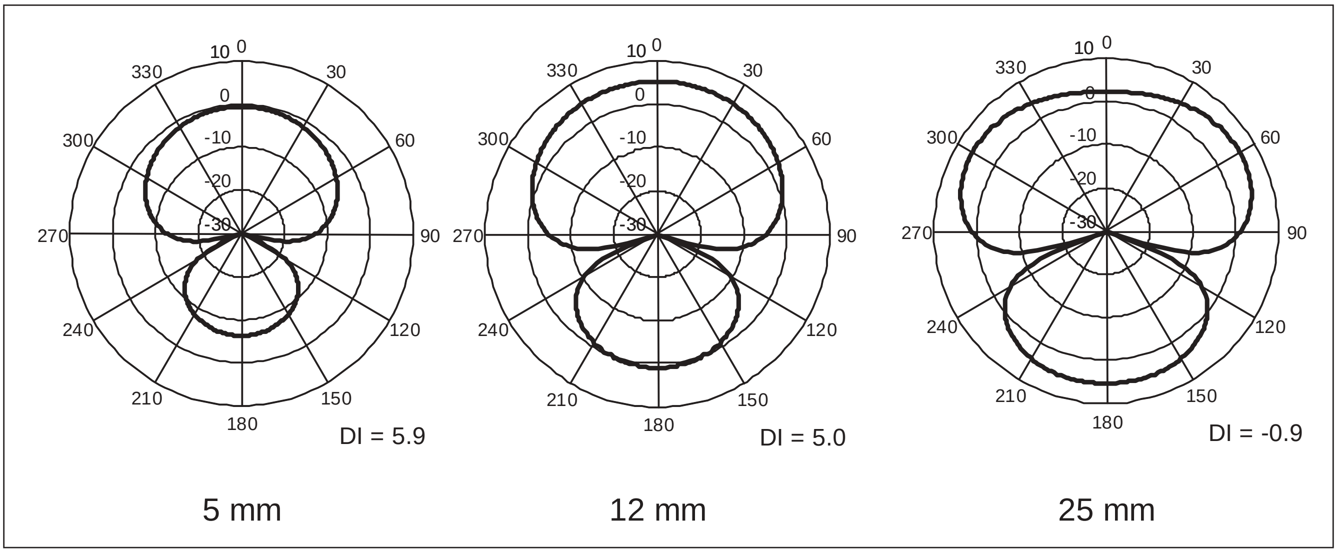


Fig. 6. Directivity pattern at 8000 Hz of a directional unit consisting of two omnidirectional microphones spaced at 5 mm, 12 mm and 25 mm. The internal delay is adjusted to render a hypercardioid pattern with perfect amplitude and phase match.

rectional microphone cannot effectively subtract the wind noise from both microphone inlets to minimize its magnitude. Rather, wind noise from both microphone inlets is added to further increase the intensity of the noise. Indeed, given a choice, many wearers would prefer an omnidirectional microphone instead of a directional microphone in open areas or where even a moderate amount of wind is present.

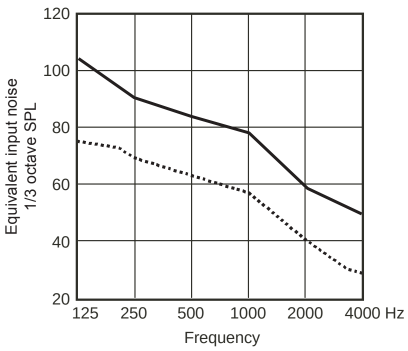


Fig. 7. Wind noise: Equivalent input noise levels measured in third-octave bands for a BTE hearing instrument equipped with a directional microphone (solid line) and an omnidirectional microphone (dashed line). Data from Dillon et al.[15] using KEMAR.

Fig. 7 shows the equivalent input noise level from two BTE hearing instruments when wind at a velocity of 5 m/s is directed towards them from the front.[15] It can be seen that wind noise has a broad frequency spectrum with a low frequency emphasis. In addition, its level is about 20 dB higher in the directional microphone mode than the omnidirectional microphone mode. This may be the reason why in such situations an omnidirectional microphone is preferred. The effect is similar whether the directional microphone is made of one or two microphones. Whereas a dedicated directional system would remain in the directional mode all the time, a dual-microphone system could allow the wearer to switch from the directional mode to the omnidirectional mode in this situation.

Conclusions

In developing hearing instruments with directional microphones, the designers have to consider many factors so that the resulting system produces the maximum SNR enhancement in real-life situations with the least negative side effects on audibility and noise floor.

Both the dedicated directional microphone and the dual-microphone directional systems offer potentially the same directional advantages and both have specific pros and cons. Additionally, both can suffer from problems with circuit noise and wind noise. Although a dual-microphone system allows its wearers to switch from the directional mode to an omnidirectional mode to ensure audibility in quiet and to minimize the effect of wind noise, the authors believe that doing so is contingent on the matching of the two microphones and the ability of the wearer to make the appropriate switch.

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