CROSSLINK DIRECTIONALITY 2: DIRECTIONALITY THAT SUPPORTS NATURAL AUDITORY PROCESSING

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Beltone™

A supercomputer can beat a human at chess but does it know what that human would like to eat for lunch? A computer that has followed the preferred eating patterns of a person over time could probably make a good guess, but would still guess incorrectly much of the time. There are many examples of how intelligence built into computers and smart devices is learning our routines and attempting to make our lives easier. Hearing aids are no exception. While most of the processing capabilities in hearing aids are dedicated to amplifying and treating the sound, there are also algorithms that control the sound processing based on observations of the acoustic input. And just like the super computer and eating patterns, a hearing aid can make the wrong guess with regard to what signal a user might want to hear. These wrong guesses can make it harder for users of hearing aids to hear what they want to hear. This is why Beltone has for a decade focused on how technology can be leveraged to let hearing aid users hear better in noise, but still hear all sounds around them similar to how a normal hearing person would hear.

One type of automatic control that every modern hearing aid has is for directional processing. This refers to decision-making by the hearing aid system to change the microphone mode of the hearing aid such that it provides an omnidirectional or a directional response. With automatic control of the microphone mode, the hearing aid wearer can potentially benefit from directional processing without having to recognize when it would be beneficial or manually select the directional mode. But just as a computer may not know what you want for lunch, a hearing aid will not always know whether directional or omnidirectional processing is best for a given situation. This is because hearing aid intelligence cannot know the wearer's intent; what sounds are important to the individual at any given moment are individual and not predictable based only the acoustic environment. Applying directionality in some situations may prevent the user from hearing sounds they actually want to hear.

How can directionality and control of directionality be accomplished with respect for the intent of the hearing aid wearer? Three factors are important in providing a seamless, natural listening experience that offers the benefits of directionality without its drawbacks. First, the decision-making algorithm is of great consequence. The rationale for selecting a particular microphone mode affects what information ultimately is provided to the user. Second, the analysis of the acoustic environment is critical. It provides the input for the decision-making about how to adapt the hearing aid processing. Finally, the directional processing itself is important. It should provide a better signal-to-noise ratio but not create issues with audibility or sound quality. Beltone CrossLink Directionality 2 was developed with careful attention to each of these three factors. Based on an accurate analysis of the acoustic environment, CrossLink Directionality 2 uniquely applies directional microphone technology to support different listening strategies, allowing the user to focus on the sounds that are important to them. Depending on the particular microphone mode, dedicated technologies serve to provide the best listening experience. Natural sound quality is central to CrossLink Directionality 2, and Band-Split Directionality ensures transparent transitions between microphone modes. In addition Personal Sound ID preserves the important localization cues that contribute to spatial hearing and the most true-to-nature sound quality. Finally, the directivity patterns of the different microphone modes are painstakingly designed, taking the acoustic properties of the head into account, to ensure that the listener can effortlessly tune in or tune out the sounds around them. CrossLink Directionality 2 optimizes the sensitivity patterns to achieve the best combination of speech from the front and spatial awareness.

When to switch? The importance of the rationale

There is no doubt that directionality in hearing aids is a measurably effective way to boost the SNR, and thus speech recognition, in noisy situations[1,2,3,4,5]. Improvements of typically 4 to 5 dB have been demonstrated in laboratory settings when the noise source is spatially separated from the speech[6] and the speech is coming from the front and is located near the listener[2,5]. However, in many daily interactions, listeners need to pay attention to sounds coming from different locations. Much of any individual's active listening time during the course of a day will not be spent facing what they want to hear. Cord et al[7] found that hearing aid wearers judged the signal of interest to come from another direction than in front more than 30% of the time. In this study, participants also indicated that the direction of sound sources was "multiple" in some listening situations, which indicated that the sound of interest either moved, or that there were more target sounds, or both.

This means that a system that automatically switches to directionality on both ears in noisy situations – even if the system also includes speech detection – is going to be reducing audibility of desired sound sources much of the time. Although people constantly and naturally turn their heads toward the sound of interest, real-world environments are unpredictable, and salient sounds can come from any direction at any time. Research on turn-taking in conversations across[10] different world languages shows that talkers switch turns in less than half a second regardless of culture and language. Attention is required to keep up with this behavior as a listener[8]. Working memory for an individual is limited, and if resources are spent on searching and orienting behaviors, fewer are available for actual listening and understanding. Considering this, using directionality can also be disadvantageous, as it cannot provide the same audibility and awareness of surrounding sounds that people with normal hearing naturally experience.

For nearly a decade as the hearing aid industry focused on developing directional microphone technology that maximizes SNR benefit in contrived and controlled environments, Beltone has followed a unique path in applying directional microphone technology. Inspired by investigations that explored real-life usage and preferences for omnidirectional and directional microphone modes, Beltone researchers worked with external partners to study and validate a different approach to applying directionality that would allow hearing aid users to hear better in noise without robbing them of awareness of their surroundings[9]. Because listeners rely on the ear with the best representation of what they want to hear in noisy surroundings, one idea that was explored was to provide directionality on one ear, and omnidirectionality on the other. It was demonstrated that this provides directional benefit that is nearly equivalent to directionality on both ears[10], while the omnidirectional ear allows the listener greater audibility of their surroundings than directionality on both ears. Amazingly, the different information from the two ears fit with an asymmetric microphone strategy was perceived as one integrated auditory image, and allowed the listener to focus on sounds, monitor sounds, and shift attention to different sounds at will. Issues with this microphone mode fitting strategy were that some situations could be encountered where bilateral directionality would provide slightly more benefit, and that speech of interest to the listener might occur on the side of the directional ear and not be sufficiently audible. Eventually, the development of ear-to-ear communication on the proprietary Beltone 2.4GHz digital wireless platform enabled two hearing aids to work as a system and to solve these issues.

Beltone continually refines its approach to using directional technology in a way that considers how listeners will experience it in real-life. A hearing aid user is not just two ears. Therefore, the entire human auditory system is considered in the design, from the acoustic effects of the shape and location of the external ears on the head to the power of binaural processing by the brain. The ultimate goal is not to give hearing aid wearers "better than normal" hearing in restricted situations. It is for hearing aid wearers to effortlessly engage in auditory social behaviors in the same way as a normal hearing individual, and thereby have a natural and transparent hearing experience.

CrossLink Directionality 2 is a microphone mode control strategy that meets the goal of providing a natural hearing experience. Like Crosslink Directionality[11] it steers the microphone configuration of two hearing instruments to support binaural sound processing by the brain. It is the only truly binaural strategy, taking advantage of scientifically proven listening strategies incorporating acoustic effects and auditory spatial attention strategies[12,13,14,15,16].

CrossLink Directionality 2 uses 2.4 GHz wireless technology to coordinate the microphone modes between both ears for an optimal binaural response. Front and rear speech detectors on each hearing instrument estimate the location of speech with respect to the listener. The environment is also analyzed for the presence or absence of noise. Through wireless transmission, the decision to switch the microphone mode for one or both of the hearing aids is made based on the inputs received by the four speech detectors in the binaural set of devices. The possible outcomes include a bilateral omnidirectional response with Personal Sound ID, a bilateral directional response, or an asymmetric directional response. These outcomes were derived from external research regarding the optimal microphone responses of two hearing instruments in different sound environments.

Environmental analysis: the best speech recognition in noise

Hearing aids have become marvels that adapt the amplification they provide to take into account the acoustic environments in which they are used. All of these hearing aids, regardless of manufacturer, attempt to recognize sounds that are likely to be either important or not important to the user. The way this is accomplished is defined by each manufacturer, although all systems will at least try to identify environments that are quiet, ones that contain speech, and ones that contain noise. Some may also attempt to further characterize types of noise or to identify music. Because decisions about how hearing aid settings should be adapted depend on how the environmental classification system identifies different sounds, it is of great interest to consider how well the classification matches up with well-defined environments. This can give an indication of how likely the system is to make changes appropriately.

The Beltone environmental recognition system uses sophisticated speech and noise detection algorithms based on input level, frequency content and spectral balance, as well as the temporal properties of the incoming sound to determine the nature of the acoustic surroundings. Furthermore, the classification does not occur according to stringent predetermined criteria, but rather on the basis of probabilistic models. To examine the accuracy of this system compared to other hearing aid environmental classification systems, the most advanced hearing aid from each of six manufacturers was placed in an Otometrics Aurical test chamber and exposed to different, well-defined sounds for periods of 2 to 22 hours. The sound recordings were looped during the exposure period to ensure consistency of the input. After each period of exposure, the hearing aid was connected to the manufacturer's fitting software, and the result of the environmental classification was read out in the data logging screen.

The sound environments consisted of the following. All sound recordings except "Quiet" are found as part of the sound library in the Otometrics OtoSuite software:

- Quiet: no input
- Noise: Hand-mixer at 75 dB SPL
- Noise: White noise at 75 dB SPL
- Noise: speech babble at 75 dB SPL
- Speech-in-noise: conversation in café noise background at 75 dB SPL
- Speech-in-noise: conversation in train station noise background at 75 dB SPL
- Speech-in-noise: conversation in party noise background at 75 dB SPL
- Speech-in-noise: conversation in supermarket noise background at 75 dB SPL
- Pop music at 65 dB SPL
- Classical music at 65 dB SPL

All systems identified quiet, speech, and white noise with a very high degree of accuracy. At least 96% of the hours of exposure in these environments were classified correctly across manufacturers. Some differences were noted for the speech babble and hand mixer noises, as shown in Figure 1. One system identified 60% of the hours exposed to the hand mixer noise as "speech-in-noise", while another classified 96% of the hours exposed to speech babble as music.

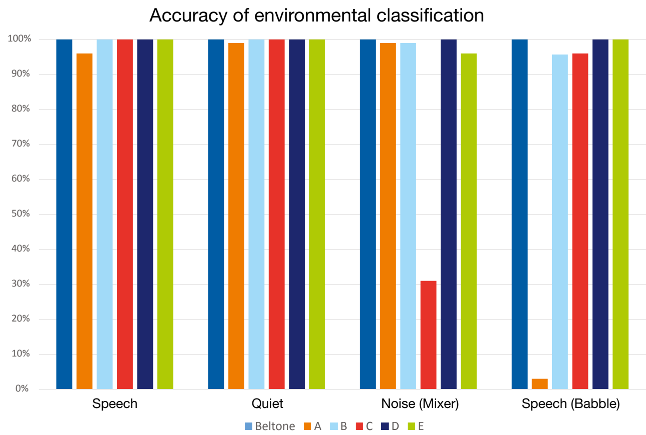

Figure 1. The environmental classification systems tested could accurately identify quiet and speech in quiet. Most could also identify different noises and speech babble as well, although some serious identification were observed.

The acoustic environments that present the greatest challenges for hearing aid users are those with background noise. Algorithms that control directionality aim to provide benefit particularly in situations where there is speech in a noisy environment. Real world environments can consist of all kinds of different background noise, and often speech is both the sound of interest as well as the competing noise. Therefore, four different background noise environments were used in this test. In each case, the "speech" was the same male and female voices having a conversation. Figure 2 presents the results combined for all four environments. The Beltone system was 98% accurate in identifying speech-in-noise, which was the highest degree of accuracy across the six systems tested. One other system also demonstrated high accuracy, with 91% of the hours exposed classified correctly. The other systems were less accurate, with 60% or fewer of the hours exposed classified correctly.

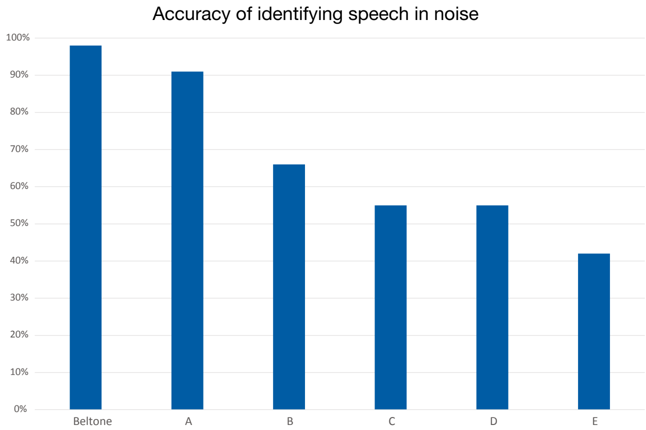

Figure 2. Beltone was 98% accurate in identifying speech-in-noise in varying noise backgrounds. No other system was as accurate, and noise backgrounds with music or highly modulated noises posed the greatest difficulty for these systems. Accurate identification of speech in noise and other environments is important in adjusting environmentally dependent parameters accurately.

An interesting finding was that the systems differed significantly in terms of which noise background caused them to be inaccurate in the classification. All were at least 75% accurate in identifying speech-in-noise for the "party" and "train station" background noise, while the "café" and "supermarket" background noise posed difficulties. The competing noise for both "café" and "party" is people talking in the background. However, "café" also includes the clinking of cups and saucers as would be typical in this environment. The classification mistakes that were made in this environment were to assign many of the hours to the "speech" category. It may be that the systems were fooled by the transient and modulating sounds caused by the cups and saucers, wrongly identifying this as speech with no competing noise.

The results from the "supermarket" background were quite inaccurate for the four systems that have a music category in their classification system. This background includes some soft music along with other typical supermarket sounds. Of the four systems with music classification, two assigned 100% of the hours exposed to the music category, one 84% of the hours, and one 37%. Taken together with the inaccuracy of the classification when these hearing aids were exposed to music (Figure 3), this calls into question the relevance of hearing aids identifying music at all. For example, while system E accurately identified 100% of the hours of both classical and pop music, it also identified 100% of the speech in the supermarket background noise environment as music. This is a thought-provoking result that illustrates how hearing aid intelligence cannot accurately predict the user's intent. The presence of music in an environment does not mean that the user wants to listen specifically to it, and may in fact consider the music to be competing noise depending on the situation.

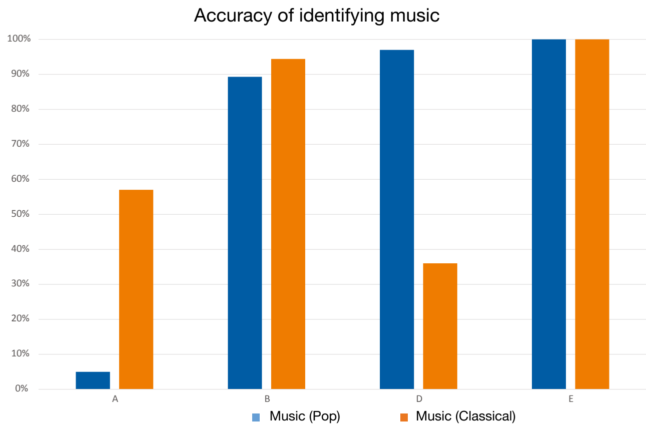

Figure 3. Four of the systems tested had music identification, presumably to automatically adjust settings for music listening. Systems B and E showed the best results in identifying two different genres of music. System E, while correctly identifying both classical and pop music, also classified 100% of speech in the supermarket background as music. It would probably not be consistent with listener intent to change to music listening settings in a supermarket environment.

Balancing directional benefit with a natural listening experience

It is well-accepted that one set of hearing aid parameters will not meet the listening needs of an individual in all conditions. This is the rationale for multi-memory hearing aids as well as automatic adaptation of hearing aid features. While the goal of fitting prescriptions is to provide amplification for optimum speech understanding while ensuring comfort for loud sounds, hearing aid users will still want to enhance or diminish different aspects of the amplified sound in different situations. One simple example is that a hearing instrument wearer might desire more volume than prescribed in an important meeting at work, but wish for less volume when relaxing with the newspaper on the train ride home several hours later. Automatic transitions among hearing aid settings is a way to account for situational preferences in a way that is effortless for the user. While this sounds ideal in theory, it may not be so in practice. Hearing aids that make abrupt or noticeable transitions in sound processing can be distracting and annoying. Some users may even think that noticeable automatic changes indicate a malfunctioning device. Therefore, Beltone strives to design automatic functionality so that it is transparent for users. They should not know when the hearing aids are in which mode. They should just be able to hear and focus on what they want. This guiding principle is part of the reason why Beltone hearing aids provide superior sound quality[17].

Importance of the directional processing

The goal of providing a transparent listening experience has implications for the sound processing in the hearing aids. Dual microphone directionality is an example of sound processing that can draw attention to itself when it is activated and deactivated automatically. Because of the close spacing of the microphones in hearing aids relative to the wavelengths of low frequency sounds, directional processing will tend to cancel low frequencies regardless of the direction of arrival of the sound. The resultant low frequency roll-off in the response creates a tinny sound quality that is different than the sound quality of an omnidirectional response. If the roll-off is compensated by boosting the low frequency gain, the noise floor of the device is also boosted. This can make the directional mode sound noisier than the omnidirectional mode. This means that no matter which approach is taken, the directional response will have a different sound quality than the omnidirectional response. The user may perceive this difference and may even be bothered by it. One way to circumvent this sound quality issue is to apply directional processing to only the high frequency portion of the input. This is what Band-Split Directionality does, and it provides equivalent sound quality between directional and omnidirectional microphone modes[18].

Given that directionality is the only proven technology to improve speech understanding in noise[19] the "more-is-better" approach of maximizing directionality across frequencies might lead one to expect better speech recognition in noise performance with full directionality than with Band-Split Directionality. On the other hand, articulation index theory would predict a negligible difference between the two types of processing, as added audibility in the lower frequencies should represent only a modest contribution to intelligibility[20]. Figure 4 shows results from a clinical investigation which supports the latter view[18]. In this study participants were fit with either open or occluding fittings and varying settings of Band-Split Directionality. Speech recognition in noise was assessed for all conditions. Regardless of the Band-Split Directionality setting or whether the fittings were open or occluding, the directional benefit was significant compared to omnidirectionality (Figure 4). For those with open fittings, the SNR improvement compared to the omnidirectional response was the same for all Band-Split Directionality settings. This was an expected finding, as the open fitting allows low frequency sound to enter the ear canal that will be audible to individuals with mild hearing level thresholds in the low frequencies. This naturally limits the potential directional benefit that can be provided in the low frequencies, and is consistent with other reports of directional benefit in open-fit hearing aids[21,22,23]. For the participants with occluding fittings, decreasing the Band-Split Directionality frequency yielded incrementally better speech recognition in noise scores. For this reason, the Band-Split Directionality setting is prescribed based on hearing loss to ensure the best balance between maximizing directional benefit and transparent sound quality between microphone modes. These findings support that providing directionality in the frequency area with the most crucial speech information makes the biggest difference in SNR improvement.

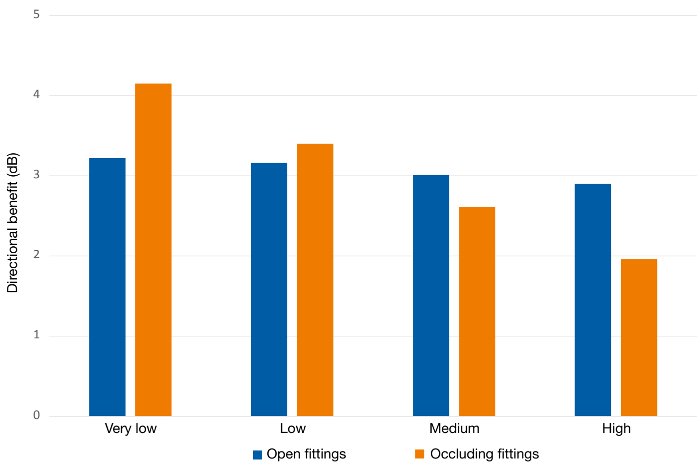

Figure 4. Directional benefit as determined by speech recognition in noise testing is mostly affected by amplification in the high frequencies. For those with more severe hearing losses and occluding fittings, added incremental benefit is observed as the Band-Split Directionality frequency is decreased. For this reason, the Band-Split Directionality frequency is prescribed for the individual.

Omnidirectional is also a kind of directional

It is not uncommon to talk about directional and omnidirectional microphones as if they somehow are opposites. However, this is not really the case. These terms describe the spatial directivity patterns of each type of microphone. A directional microphone amplifies sound coming from a particular direction more than sounds coming from other directions, while an omnidirectional microphone amplifies sounds equally regardless of which direction they come from. Directional microphone systems in modern digital hearing aids are usually dual microphone systems, where two omnidirectional microphones are positioned on the device, and digital delays are applied to one of the microphones to create the desired spatial directivity patterns. Virtually any type of directional patterns can be created with this technology, including omnidirectional patterns if that is desired.

But what happens to spatial directivity patterns when a hearing aid is worn? Figure 5 shows the spatial directivity patterns for an omnidirectional microphone measured on the head. Low frequencies travel easily around an obstacle such as a human head with little attenuation. They are quite omnidirectional even with the hearing aid placed on the right ear, meaning that there is little attenuation of those frequencies regardless of direction of arrival. However, for high frequency sounds arriving from the left side, there is a great deal of attenuation caused by the head shadow. While the head shadow effect is helpful for both localization in quiet surrounding as well as for helping us hear better in noise, the CrossLink Directionality 2 strategy seeks to balance access to an improved SNR with access to sounds in the surroundings. This means that the head shadow effect is in one way counterproductive when the hearing aid microphones have switched to an asymmetric mode. It will result in "blind spots" where some sounds from certain directions will have reduced audibility. While the head shadow effect is highly desirable on the directional ear to maximize SNR, a completely omnidirectional response would be desirable on the opposite ear to maximize access to sounds in the surroundings.

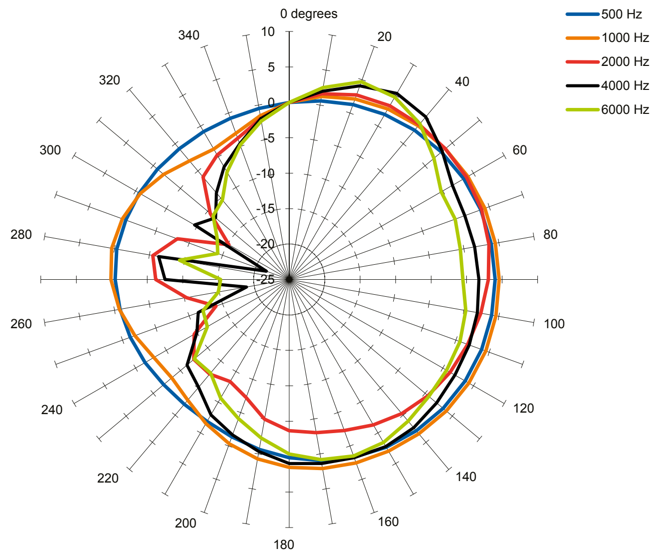

Figure 5. Spatial directivity patterns of an omnidirectional microphone measured on the right ear of a KEMAR. The patterns in the high frequencies are greatly affected by the head shadow effect such that the response is not omnidirectional.

Since the head shadow effect is an acoustic effect that cannot be changed by hearing aid processing, Beltone engineers looked again to the natural ear for inspiration in tuning the directional characteristics of both the directional and omnidirectional spatial directivity patterns to achieve the most natural balance of hearing better in noise with environmental awareness.

A new method to optimize the system

As discussed previously, the human auditory system relies on inputs from two ears, and binaural benefits are derived by comparing and integrating the differing inputs from the two ears. In designing a directional system that supports natural hearing processes, it therefore makes sense to first examine the combined acoustic effects of the two ears and their placement on the head. This information can then be used as a reference for benchmarking the system design. Hearing care professionals are familiar with the Directivity Index (DI), a metric which quantifies the relative amplification of sounds originating from a zero-degree azimuth to sounds arriving from other azimuths. The DI is commonly used to describe the effect of directional processing in hearing aids. However, the DI is a poor indicator of how binaural effects will contribute to improvements in SNR because it describes the characteristics of only one device. Furthermore, the DI is only an indication of how SNR can be improved for sounds coming from in front of the listener. Because the rationale of CrossLink Directionality 2 is to allow listeners to use either a better ear or awareness listening strategy, it is also crucial to include a measure of awareness in evaluating the system design.

To assist in creating the optimum design, Beltone researchers proposed a method to acoustically map out the spatial patterns combining the left and right ears and, based on the directional patterns of the two ears, quantify both how the system contributes to improved SNR as well as situational awareness[24]. Essentially, two new DI concepts were introduced. One is to include the effects of both ears in calculating the DI rather than one ear alone. The other is to calculate a sort of “reverse” DI that also includes both ears, thereby providing an indication of environmental awareness. Figure 6 illustrates these concepts for open ears on the head. Note how the “Better ear index”, which is the binaurally calculated DI, provides better SNR enhancement than the single ear DI. By the same token, the “Situational awareness index” is much lower than the single ear DI, illustrating how binaural acoustic effects can provide greater audibility for sounds regardless of direction of arrival. These two indices have served as a benchmark for design of the spatial directivity patterns for CrossLink Directionality 2. The design goal was to maximize the Better ear index, while preserving a Situational Awareness index that was similar to open ears. For the hearing impaired individual, this would provide access to an enhanced SNR, while maintaining access to environmental sounds not originating from in front.
In-house studies with human listeners have validated that these metrics are strongly correlated with perception. That is, a high Better ear index relates to better speech-recognition-in-noise for signals presented from in front of the listener, while a low Situational awareness index correlates with better audibility for off-axis sounds.

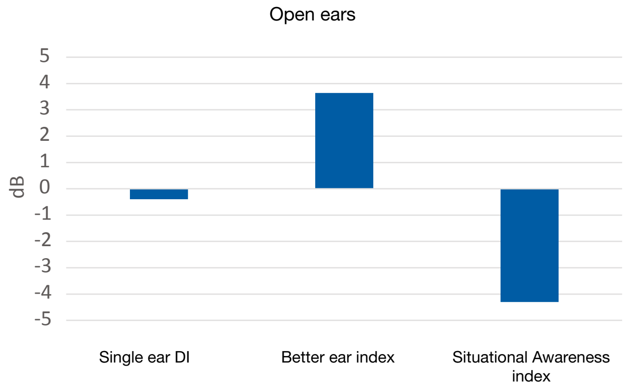

Figure 6. The Better ear index and Situational awareness index capture binaural acoustic spatial directivity patterns. A traditional DI accounts for the effects of only one ear. The Better ear index and Situational Awareness index can together serve as a benchmark for evaluating system design.

Figure 7. CrossLink Directionality 2 provides an improved SNR relative to the open ear but maintains awareness of sound in the environment, as indicated by the new metrics. This sets the stage for a natural listening experience. A solution with narrow directionality using a 4-microphone array provides a high single ear DI but little added binaural benefit, and reduces audibility of off-axis signals. This results in an unnatural listening experience.

Supporting spatial hearing

Spatial hearing refers to the listener’s ability to segregate the incoming stream of sound into auditory objects, resulting in an internal representation of the auditory scene, including the aspect of spaciousness. An auditory object is a perceptual estimate of the sensory inputs that are coming from a distinct physical item in the external world[25]. For example, auditory objects in a kitchen auditory scene might include the sound of the refrigerator door opening, the sound of the water running in the sink, and the sound of an onion being chopped. The ability to form these auditory objects and place them in space allows the listener to rapidly and fluidly choose and shift attention among these objects. Furthermore, the formation of an auditory scene provides a natural-sounding listening experience.

The auditory system must construct this spatial representation by combining multiple cues from the acoustic input. These include differences in time of arrival of sounds at each ear (Interaural Time Difference – ITD), differences in level of sounds arriving at each ear (Interaural Level Difference – ILD) as well as spectral "pinna" cues. Head movements also are important contributors as the auditory system quickly analyzes how the relationships among these cues change. Disrupting any of these cues interferes with spatial hearing, and it is known that hearing aids may distort some or all of them.

Personal Sound ID is a unique Beltone technology that accounts for the three hearing instrument-related issues that can interfere with spatial cues:

1. Placement of the microphones above the pinna in Behind-the-Ear (BTE) and Receiver-in-the-Ear (RIE) styles removes spectral pinna cues[26,27].

2. Placement of the microphones above the pinna in BTE and RIE styles distorts ILD[28].

3. Independently functioning Wide Dynamic Range Compression in two bilaterally fit hearing instruments can distort ILD [29].

Personal Sound ID[11] is modeled after the natural ear including pinna restoration for an accurate estimate of ILD, wireless exchange of information to emulate the crossing of signals between ears, and the correction of ILD based on the ear with the least intense signal to emulate inhibitory effects of auditory efferent effects. With preserved localization cues, Personal Sound ID adds to the natural listening experience and superior sound quality provided by Beltone technologies.

Summary

A natural hearing experience depends on the brain receiving distinct signals, which can be compared and contrasted to segregate the stream of acoustic information into a meaningful picture of the sound environment. The differences and similarities between sounds arriving at each ear can be used to enhance or suppress environmental sounds at will, and lets us easily shift our attention among these sounds. Depending on what the sound of interest is at any particular moment, we innately use different listening strategies, and we unconsciously change between a strategy that relies on environmental awareness and one that relies on the ear with the best representation of the interesting sound. A person changes their listening strategy from "awareness" to "better ear" when they lean closer to the sound they want to hear, turn one ear more toward the sound, or cup their ear with a hand. Most advanced hearing aids use technology to "short circuit" these natural hearing strategies in an attempt to enhance a particular sound that is determined by artificial intelligence to be the most important. In stark contrast, CrossLink Directionality 2 uniquely applies directional microphone technology to support both the awareness and better-ear listening strategies. Ear-to-ear wireless communication facilitates an analysis of the environment, which is used to automatically select the optimum of 4 bilateral microphone modes to support both listening strategies. Depending on the particular microphone mode, dedicated technologies serve to provide the best listening experience. Natural sound quality is central to CrossLink Directionality 2, and Band-Split Directionality ensures transparent transitions between microphone modes. In addition, Personal Sound ID preserves the important localization cues that contribute to spatial hearing and the most true-to-nature sound quality. Finally, the directivity patterns of the different microphone modes are painstakingly designed, taking the acoustic properties of the head into account, to ensure that the listener can effortlessly tune in or tune out the sounds around them. CrossLink Directionality 2 optimizes the sensitivity patterns to achieve the best combination of speech from the front and spatial awareness. CrossLink Directionality 2 provides the ultimate balance for supporting natural hearing: a signal-to-noise ratio improvement similar to bilateral directional microphones and a significant benefit in ease of listening compared to other directional microphone strategies.

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