Binaural Directionality III: Directionality that supports natural auditory processing

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ABSTRACT
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. Binaural Directionality III 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. This paper reviews the rationale for Binaural Directionality III and how it achieves this balance.

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 ReSound 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.

ReSound Binaural Directionality III was developed with careful attention to each of these three factors. Based on an accurate analysis of the acoustic environment, Binaural Directionality III 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 Binaural Directionality III, and Directional Mix ensures transparent transitions between microphone modes. In addition Spatial Sense 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 effort- lessly tune around the advantages of the omnidirectional. However, in 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. 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 di- rection of sound sources was “multiple” in some listening situa- tions, 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 – could 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 different world languages shows that talkers switch turns in less than half a second regard- less of culture. Of course, it is not possible to keep up with this behavior as a listener. 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 devel- oping directionality, microphones that maximize SNR benefit in continuous environments have been developed. ReSound has followed a unique path in applying directional microphone tech- nology. Inspired by investigations that explored real-life usage and preferences for omnidirectional and directional microphone modes, ReSound 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. Because lis- teners 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 omnidirectional- ity on the other. It was demonstrated that this provides direc- tional benefit that is nearly equivalent to directionality on both ears, while the omnidirectional ear allows the listener greater audibility of sounds in the environment. Amazingly, the different information from the two ears fit with an asymmetric microphone strategy was perceived as one in-tegrated 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 direc- tionality 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 ReSound 2.4 GHz digital wireless platform enabled two hearing aids to work as a system and to solve these issues. ReSound 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. There- fore, the entire human auditory system is considered in the de- sign, 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 wear- ers “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.

As the name implies, Binaural Directionality III is the third gen- eration of the microphone mode control strategy that meets the goal of providing a natural hearing experience. Like Binaural Directionality II, it uses 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 acous- tic effects and auditory spatial attention strategies.4,11,13,19

Binaural Directionality II 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 communication, 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 possi- ble outcomes include a bilateral omnidirectional response, a Spatial Sense, a bilateral directional response, or an asymmet- ric directional response. These outcomes were derived from ex- ternal 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 set- tings should be adapted depend on how the environmental classification is performed in laboratory settings, 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 ReSound environmental recognition system uses sophis- ticated 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 classi- fication does not occur according to stringent predetermined criteria, but rather on the basis of probabilistic models. To ex-amine 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 Omnetics OmSuite software environment. The system evaluated six types of environmental classification systems: Binaural Directionality II, Binaural Directionality III, Spatial Sense, a bilateral omnidirectional response, a bilateral directional response, or an asymmet- ric directional response. These outcomes were derived from ex- ternal research regarding the optimal microphone responses of two hearing instruments in different sound environments.

The acoustic environments that present the greatest chal- lenge 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 en- vironment. 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 dif- ferent 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 each of all four speech-in-noise environments. The ReSound system was 98% accurate in identifying speech-in-noise, which was the highest degree of accuracy across the six systems tested. One of the six systems 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.

SPEECH RECOGNITION IN NOISE

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 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 manu- facturers. Some differences were noted for the speech bab-
An interesting finding was that the systems differed significantly in terms of which noise background caused them to be inaccurate in their 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 classifi-
cation when these hearing aids were exposed to music (Figure 3), this calls into question the relevance of hearing aids identifying both classical and pop music, also classified 100% of the hours of both classical and pop music, it also identifying 100% of the hours of each of the background noise environments 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.

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 especially true for multi-microphone 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, ReSound 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 ReSound hearing aids have been top-rated for sound quality.

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 directionalism is an example of sound processing that can draw attention to itself when it is activated and deacti-
vated automatically. Because of the close spacing of the micro-
phones in hearing aids relative to the wavelengths of low fre-
quency 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 tiny 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 Directional Mix does, and it provides equivalent sound quality between directional and omni-
directional microphone modes.

Given that directionality is the only proven technology to im-
prove speech understanding in noise18 the “more-is-better” ap-
proach of maximizing directionality across frequencies might lead one to expect better speech recognition in noise perfor-
mance with full directionality than with Directional Mix. On the other hand, articulation index theory would predict a negligible difference between the two types of processing, as added au-
dibility in the lower frequencies should represent only a modest contribution to intelligibility. Figure 4 shows results from a clinical investigation which supports the latter view19. In this study participants were fit with either open or occluding fittings and varying settings of Directional Mix. Speech recognition in noise was assessed for all conditions. Regardless of the Direc-
tional Mix setting or whether the fittings were open or occlud-
ing, the directional benefit was significant compared to omni-
directional (Figure 4). For those with open fittings, the SNR improvement compared to the omnidirectional response was the same for all Directional Mix 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 hear-
ing 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-fitting hearing aids20,21. For the participants with occluding fittings, increasing the Directional Mix setting yielded incrementally better speech recognition in noise scores as Di-
rectional Mix was increased. For this reason, the Directional Mix setting is prescribed based on hearing loss to ensure the best balance between maximizing directional benefit and transpar-
tent sound quality between microphone modes. These findings support that providing directionality in the frequency area with the most crucial speech information makes the biggest differ-
ce in SNR improvement.

Omnidirectional is Also a Kind of Directional

It is not uncommon to talk about directional and omnidirec-
tional microphones as if they somehow are opposite. How-
ever, this is not the real case. These terms describe the spatial directivity patterns of each type of microphone. A directional microphone amplifies sound coming from a particular direc-
tion more than sounds coming from other directions, while an omnidirectional microphone amplifies sounds equally re-
gardless of which direction they come from. Directional micro-
phone 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 cre-
aled with this technology, including omnidirectional patterns if that is desired.

But what happens to spatial directivity patterns when a hear-
ing 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 di-
rection 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 Binaural Directionality III 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 mi-
crophones 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 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. This would not be consistent with listener intent to change to music listening settings in a supermarket environment.

Figure 4. Directional benefit as determined by speech recognition in noise test-
ing is increased by amplification in the high frequencies. For those with more severe hearing losses and occluding fittings, added incrementality benefit is observed as the Directional Mix is increased. For this reason, Directional Mix is prescribed for the individual.

Figure 5. Spatial directivity patterns of an omnidirectional microphone mea-
sured on the right ear of a KEMAR. The patterns in the high frequencies are greatly af-
fected by the head shadow effect such that the response is not omnidirectional.
A NEW METHOD TO OPTIMIZE THE SYSTEM

As discussed previously, the human auditory system relies on inputs from both ears. 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 Binaural Directionality III 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, ReSound researchers proposed a method to acoustically map out the spatial patterns by 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.

In designing a directional system that supports natural hearing, the researchers first examined the sensory cues that contribute to improvements in SNR as well as situational awareness.

In order to form these auditory objects and place them in space allows the brain 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 to the natural listening experience and superior sound quality provided by Surround Sound by ReSound technologies.
REFERENCES


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