Enhanced directional strategy with new binaural beamformer leads to vastly improved speech recognition in noise

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ABSTRACT

Hearing aids can improve many aspects of life quality for users, but hearing well in noise remains an area where users may struggle. Directional microphones in hearing aids can help, but also have the potential to interfere with users' ability to follow conversations or keep tabs on their environment. Unwanted impact on sound quality can also be a drawback. The Tailored Hearing philosophy followed by Beltone guides a binaural strategy for applying directionality that considers how the brain naturally uses different ways of listening depending on users' listening goals in different situations, as well as users' sound quality preferences. With the Beltone Achieve, we introduce enhanced directional technology and better control of automatic switching. In this paper we describe how CrossLink Directionality 4 and Ultra Focus 2 can provide an astounding 150% improvement in speech recognition in noise compared to legacy technology while still allowing for auditory awareness of the surroundings.

Wearing hearing aids improves hearing-related quality of life and ability to communicate.[1,2] People who wear hearing aids often report that the enrichment they have experienced makes them wish they had not waited so long to acquire them.[3] Further, they recognize that not adopting hearing aids when they are needed is more stigmatizing than using them.[4] Although there are many positive effects of wearing hearing aids, they can still be improved. Many ideas for improving hearing aids focus on the continued issue of helping people hear better in noisy situations.

Directional microphones in hearing aids are a technology that is proven to increase signal-to-noise ratio and speech recognition for speech in front of the hearing aid user.[5] Much attention has been dedicated to exploring factors that affect the benefit of directionality, and development efforts have largely focused on how to make them work even better. With our Tailored Hearing approach, Beltone has followed a unique path in applying directional microphones in hearing aids that supports the ways that people naturally listen in different types of situations. This involves considering not only the acoustics of the environment, but also what the listening intent of the person in that situation could be.

For example, imagine stopping at a busy café with a few friends. There are at least three distinct listening goals that would be relevant in this situation. First, you need to place your order and pay for it, which requires focusing on the person who waits on you. Second, you may chat with one of your friends while also listening for your name to be called when your order is ready. This requires selective attention to your friend while also monitoring the environment to catch your name being called. Finally, you will want to follow the lively conversation with your friends when you sit down and enjoy your order. This requires distributing and shifting your attention. In all these cases, the acoustic environment does not change much, but how you are using your hearing does. Recent research is shedding light on how our brains act differently depending on how we want to listen. Studies using physiological methods to measure brain activity when different types of listening strategies are used indicate that the specific strategy differentially activates areas of a connected network of brain regions responsible for auditory association, attention, and speech processing.[6] This further suggests the importance of not applying a "one-size-fits-all" approach to directionality where it is assumed that a user's listening goals depend only on acoustic environment.

The Beltone strategy for applying directional microphone technology is to automatically select one of three listening modes that is most likely to provide benefit without interfering with the user's listening goals in their current surroundings.[7,8] These modes and the rationale for each are shown in the table.

LISTENING MODE	Rationale	Technical detail
Spatial Cue Preservation	Emphasizes naturalness and overall sound quality	M&RIE canal microphone and binaural compression applied to both hearing aids*
Binaural Listening	Uses the brain's binaural processing ability to shift focus without losing touch with the surroundings	Asymmetric directional response with directionality on one side and omnidirectionality on the other
Speech Intelligibility	Provides the best SNR in noisy situations where there is only detectable speech in front of the user	Bilateral directional response

TECHNOLOGY UPDATES

With the Beltone Achieve, we introduce three important updates to the technology that enables the directional strategy:

1. An improved weighted binaural beamformer with better resolution that provides a stronger directional response.
2. Streaming of sound between the hearing aids that ensures audibility and awareness all around.
3. A new steering system that selects and maintains the best listening mode even in unstable sound backgrounds.

A new automatic program, CrossLink Directionality 4, incorporates all these improvements. A new user selectable program, Ultra Focus 2, provides additional benefit compared to the legacy Ultra Focus program due to the higher resolution binaural beamformer.

Higher resolution binaural beamformer

A binaural beamformer in hearing aids relies on ear-to-ear streaming to create a highly directional, monaural signal that is usually delivered to both ears. While it is possible to improve the technical SNR at ear level via this approach, there are drawbacks when the hearing aids are worn by the user. Of great importance is the fact that binaural hearing cues that help listeners locate and separate competing sound streams in complex and realistic listening situations are eliminated with this technology. Beltone instead uses a multiband approach to preserve spatial hearing cues.[8] As shown in Figure 1, binaural beamforming is limited to a mid-frequency range that contains critical speech information. Beginning with the Beltone Achieve, finer resolution in the signal streamed ear-to-ear in this region boosts the Directivity Index (DI) by approximately 5 dB relative to the technology introduced in Beltone Imagine.

Above 5000 Hz, fixed directionality is applied independently by each hearing aid to better preserve monaural spectral cues. Below a configurable crossover frequency, omnidirectional processing is applied. While this has the advantage of preserving Interaural Timing Differences (ITD) that are important localization cues, the omnidirectional response also has effects that users can directly appreciate. These are consistent sound quality across different listening modes as well as consistent and natural own voice perception.

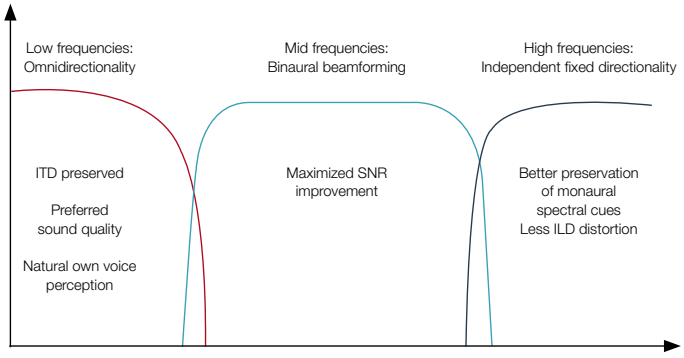


Figure 1. The Beltone binaural beamformer applies strong directionality in the mid-frequency range, while preserving spatial hearing cues in the low and high frequency bands. Omnidirectional processing in the low frequencies ensures consistent sound quality and own voice perception regardless of listening mode.

Consistent sound quality

We have shown that the sound quality of applying an omnidirectional response in the low frequencies is preferred by listeners compared to full band directionality, and that listeners judge the sound quality of bandsplit directionality with an omnidirectional response in the low frequencies as equal to a full omnidirectional response.[9,10] Therefore, it is possible to switch between Spatial Cue Preservation mode, Binaural Listening mode, and Speech Intelligibility mode without the user noticing, yet the user will benefit from each mode in the specific acoustic environment.

Consistent, natural, own voice perception

A longstanding issue with directional microphones in hearing aids is that they amplify low frequency sounds that occur up close more than sounds arriving from a greater distance. This is called the proximity effect and is illustrated in Figure 2. The user's own voice is very close to the hearing aid microphones and will therefore be amplified more relative to sounds that are further away when there is a directional response in the low frequencies; the effect is that the user's own voice sounds loud, boomy and unnatural. This is made even worse by equalizing the low frequency roll-off that is inherent in directional microphones.[11] By maintaining an omnidirectional response in the lower frequencies, both the low frequency roll-off and the proximity effect are completely avoided, and good quality of own voice is preserved regardless of which listening mode CrossLink Directionality 4 has selected. Therefore, users can hear better in any environment without distracting side effects such as the sound of their own voice being unnatural or changing in quality.

* Depending on receiver; Personal Sound ID is applied for standard receivers

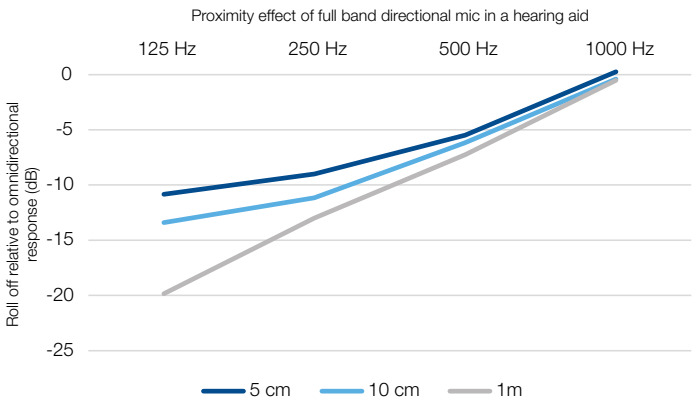


Figure 2. Directional microphones exhibit a low frequency roll-off which is dependent on the distance to the sound source. Sounds that are close to the microphones – like the hearing aid user's own voice – can sound disturbingly loud to them. Omnidirectional processing in the low frequencies with Beltone directionality avoids this proximity effect.

Awareness all around

A key concept of the Beltone directional strategy is to ensure that directional processing does not interfere with user intent. As discussed, the listening goals of people functioning in real world environments are not predicted only on the acoustics of those environments. It has been shown that the Binaural Listening mode of the Beltone directional strategy provides better audibility for off axis (not in front of the listener) speech than other premium hearing aids with binaural beamforming. This was achieved by careful design of the directional characteristics of the non-directional device in the Binaural Listening mode to compensate for the head shadow effect,[12] and has been shown to provide significantly better audibility for off-axis talkers than full bandwidth beamforming in other premium hearing aids.[7] Because of the high resolution ear-to-ear streaming capability, it is has been possible to engineer the Binaural Listening mode in CrossLink Directionality 4 for optimized audibility of sounds all around the listener by streaming the sound from the side where directionality is applied to the side where omnidirectionality is applied.

Decisiveness ensures benefit

The environmental classifier in Beltone hearing aids relies on probabilistic models to characterize the acoustic environment. This has been shown to be accurate compared to subjective judgements of the environment.[13] Decision-making on how some features, such as Sound Cleaner noise reduction, are applied using data from the classification system on a continual basis to ensure transparency as well as benefit based on our experience that users can be distracted by audible changes in hearing aid processing. Until now, steering among the listening modes of our directional strategy also has been based on probabilities. This can, however, result in very slow transitions among the different listening modes where the hearing aids are not completely in one mode or the other, potentially depriving users of the intended benefit, especially in unstable sound backgrounds.

Beginning with Beltone Achieve, a new steering system is introduced that retains the proven environmental classification, but implements a new method of switching between listening modes based on a deterministic model. This ensures clearer distinctions among the listening modes as the hearing aids are worn in real-world settings. The time needed to switch between modes has been approximately halved compared to legacy technology with transition times ranging 1 to 7 seconds faster depending on the listening mode. The result is a robust system that analyses, decidedly chooses, and maintains the appropriate listening mode based on a conservative assessment of which listening mode will support the user's most likely listening strategies.

DEMONSTRATED PERCEPTUAL BENEFITS

To document the improvements implemented in CrossLink Directionality 4 and Ultra Focus 2 compared to the legacy features in Beltone Achieve, two laboratory experiments were carried out. In both tests, fifteen individuals with bilaterally moderately sloping sensorineural hearing loss (12 males and 3 females) participated. All participants were experienced hearing aid users with a median of 12 years of experience with amplification (1st quartile: 8 years and 3rd quartile: 14 years). The median age of the participants was 73 years with a first quartile of 67 years and a third quartile of 74 years.

EXPERIMENT 1: SPEECH RECOGNITION IN NOISE BENEFIT

Methods

Hearing aids and fitting

The hearing aids tested were Beltone Achieve Receiver-in-the-ear (RIE) in omnidirectional mode, the CrossLink Directionality 4 program, and Ultra Focus 2 directionality. Beltone Achieve was benchmarked against legacy Beltone Imagine RIE in omnidirectional mode, the CrossLink Directionality 3 program, and Ultra Focus directionality. Because an open fit can reduce the benefit of directionality,[14] the hearing aids were fitted with power domes to isolate the potential benefit of CrossLink Directionality 4. The hearing aids were fit to the proprietary gain prescription.

Test material, conditions, and setup

The participants completed a speech recognition in noise test that was a slightly modified version of the Dantale II test.[15] The test is comprised of five-word sentences and was presented in a background of static speech-shaped noise at 70 dB SPL. Thirty sentences are administered for each test. The level of the speech is manipulated to determine a speech reception threshold (SRT) of 50% correct performance, resulting in a dB SNR score, with better performance revealed through lower dB SNR scores. The hearing aids tested have adaptive features that rely on identification of speech and noise in the environment. To ensure that all adaptive features were activated during testing the Dantale II test, noise was started thirty seconds before testing was initiated. The test was conducted in an idealized situation to maximize possible benefit from the directional features. Therefore, the manually selectable programs Ultra Focus 2 (Beltone Achieve) and Ultra Focus (Beltone Imagine) were used. Note that Ultra Focus 2 and Ultra Focus provide the same directional response as the

Speech Intelligibility mode in CrossLink Directionality 4 and CrossLink Directionality 3, except that the crossover frequency in the low band is fixed rather than configurable. In addition, speech material and noise band-pass was limited to 500-4000 Hz to increase task difficulty by avoiding ceiling effects.

Testing was completed with the participants seated in a sound booth with speech presented at 0 degrees azimuth, and static noise presented at 75 degrees azimuth to the right. The positioning of the competing noise in the front plane was intended to highlight the stronger directional response - which can also be thought of in terms of a more narrow directional beam - of Ultra Focus 2 compared to Ultra Focus. The setup is illustrated in Figure 3. The testing order of conditions and the sentence lists were counterbalanced across participants.

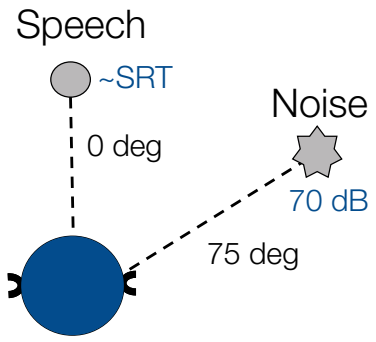


Figure 3: Test setup used for measuring SRTs with adaptive SNRs for a front talker in omnidirectional-, Ultra Focus 2 and Ultra Focus mode.

Results

Both legacy Ultra Focus and Ultra Focus 2 showed significant improvements over their respective omnidirectional modes. Of even greater interest was that Ultra Focus 2 provided a significant improvement over Ultra Focus (Paired samples t-test: $t = 6.17$, $p < 0.001$). The mean directional benefit for Ultra Focus was 4.3 dB while Front Focus provided a mean directional benefit of 8.6 dB. Ultra Focus 2 provided a significant improvement of 4.3 dB over Ultra Focus (Figure 4). By rounding this benefit up to 4.5 dB, this would represent an intensity ratio of 2.5, allowing us to estimate an incredible 150% improvement in speech recognition in noise for Ultra Focus 2 compared to Ultra Focus.

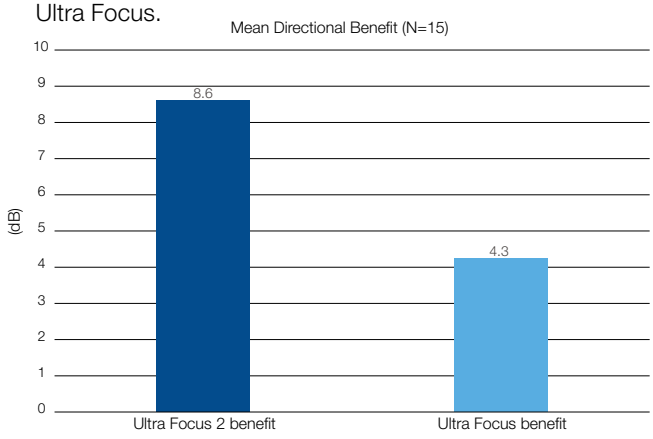


Figure 4: Mean directional benefit for Ultra Focus 2 and legacy Ultra Focus user selectable directional programs with binaural beamforming. Ultra Focus 2 and Ultra Focus give similar directional benefit to the Speech Intelligibility mode of the automatic CrossLink Directionality 4 (Beltone Achieve) and CrossLink Directionality 3 (Beltone Imagine) programs.

Directional performance for Ultra Focus 2 and Ultra Focus 2 directionality per participant can be seen in Figure 5. All but one participant gained additional directional benefit with Ultra Focus 2 compared to the directional benefit observed with Ultra Focus.

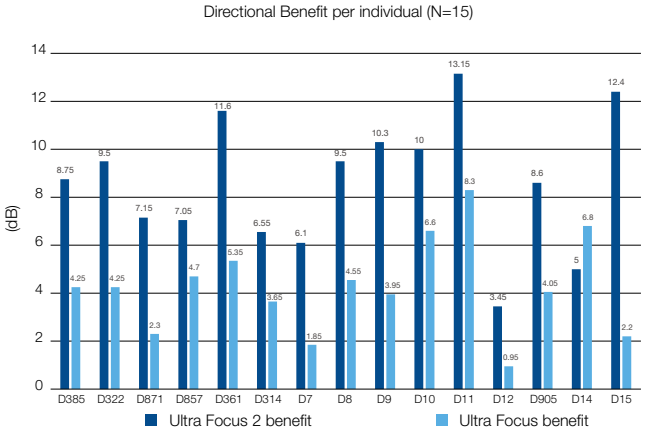


Figure 5: Ultra Focus 2 and legacy Ultra Focus performance per participant. All participants showed a minimum of 5 dB directional benefit with Ultra Focus 2, and 14 of 15 participants did better with Ultra Focus 2 than Ultra Focus.

Conclusions

Both the legacy Beltone Imagine Ultra Focus and Beltone Achieve Ultra Focus 2 directional programs provided a significant directional benefit. Ultra Focus 2 provided a highly significant improvement over Ultra Focus.

EXPERIMENT 2: ENVIRONMENTAL AWARENESS

Methods

Hearing aid fitting

In this experiment the hearing aids were fitted with a special setting that fixed them in the Binaural Listening mode of CrossLink Directionality 4 (Beltone Achieve) and CrossLink Directionality 3 (Beltone Imagine). As in Experiment 1, the hearing aids were fitted to the proprietary gain prescription and the listeners wore power domes.

Test material, conditions, and setup

The participants completed the Dantale II[15] speech recognition in noise listening test with the test modified to present the target speech off axis and with an additional competing speech signal. Testing was completed with the test participants seated in a sound booth with three loudspeakers: one at 0 degrees with male speech at 70 dB SPL, one at 270 degrees with 60 dB SPL noise and one at 120 degrees with target female speech (Figure 6). Otherwise, the test was conducted as described in Experiment 1.

Participants completed a speech intelligibility test for the Beltone Achieve CrossLink Directionality 4 Binaural Listening mode and the Beltone Imagine CrossLink Directionality 3 Binaural Listening mode conditions. Both the conditions and sentence list order were counterbalanced across participants.

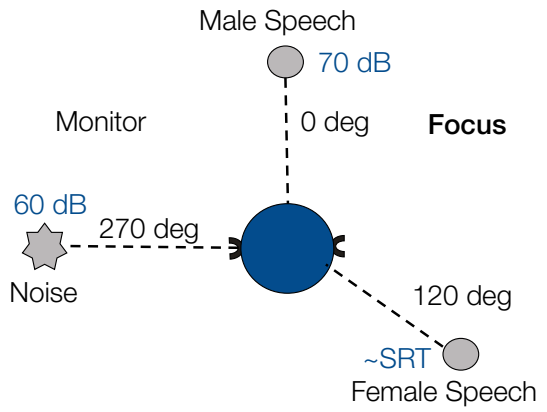


Figure 6: Test setup used for measuring SRTs with adaptive SNRs for a female talker in the rear plane in CrossLink Directionality 4 Binaural Listening mode, and CrossLink Directionality 3 Binaural Listening mode. "Monitor" refers to the ear that has a directional response that is designed to optimize audibility and, for CrossLink Directionality 3 specifically, also receives a streamed sound signal from the other device to eliminate head shadow. "Focus" refers to the ear that uses the binaural beamformer. The target female speech was located in a position where the binaural beamforming would be expected to cancel the sound.

Results

The results showed slightly better audibility for the off-axis female talker with CrossLink Directionality 4 Binaural Listening mode compared to CrossLink Directionality 3 Binaural Listening mode, although this 1.1 dB advantage was not quite significant (paired samples t-test; t = 1.69, p = 0.056). Examining individual results, 5 of the participants showed a benefit of at least 2 dB greater with CrossLink Directionality 4 than with CrossLink Directionality 3. Only one participant performed better to this degree with CrossLink Directionality 3.

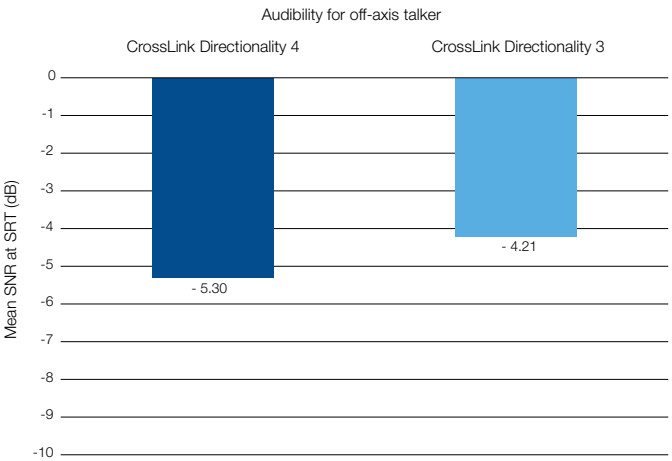


Figure 7: Mean SNR scores for a target female talker in the rear plane when in the Binaural Listening mode of the automatic directional program. Audibility was slightly, but not significantly better with CrossLink Directionality 4 than legacy CrossLink Directionality 3.

Conclusions

The Binaural Listening mode of CrossLink Directionality 4 in Beltone Achieve provided slightly, but not significantly better audibility for off axis speech than that of CrossLink Directionality 3 in Beltone Imagine. This supports that both can allow users to monitor their surroundings better than a directional response on both ears, considering that listener intent is unknown in many acoustic environments with noise. The individual results suggested that the off-axis advantage with CrossLink Directionality 4 is greater than with CrossLink Directionality 3 in those cases where a difference is demonstrated.

SUMMARY

The CrossLink Directionality 4 automatic directional program and the user selectable Ultra Focus 2 in the Beltone Achieve offer technological improvements compared to legacy directional features. These include binaural beamforming with higher resolution, ear-to-ear streaming of sound to optimize situational awareness, and a new steering system that controls switching between listening modes. Two listening experiments tested the potential benefit of the improvements for both on-axis (in front) and off-axis listening in noise. They showed that the enhanced binaural beamformer gives an improvement of 150% compared to legacy technology in the tested condition, and that audibility for sounds not in front is preserved. These results suggest that CrossLink Directionality 4 and Ultra Focus 2 will provide even better support for hearing aid users to apply natural listening strategies in their daily lives than with legacy technology.

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