# Preserving Localization through Surround Sound Processing and Remote Microphone Placement

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## ABSTRACT

Localization, or the ability to determine the position of sounds in the listening environment, is critical for successful auditory perception. However, hearing instruments often cause problems for localization, through the signal processing and/or the physical design of the instrument. ReSound has addressed this problem for both directional and omnidirectional hearing instruments in the Alera line. For directional behind-the-ear (BTE) hearing instruments, Surround Sound by ReSound processes low frequencies as omnidirectional and high frequencies as directional, to maintain important localization cues in the low frequencies. For Custom Remote Microphone hearing instruments, the placement of the microphone in the upper concha allows for natural localization abilities due to pinna effects.

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Localization is the ability to determine the source of sounds in the listening environment. Also referred to as spatial hearing, it allows the listener to place sounds in their correct locations in the environment, so that the auditory experience is natural and undistorted. It allows for the construction of auditory scenes, which relates the listener to the space and objects around him or her. When localization abilities are disrupted, listeners may report that they cannot distinguish the distance of sound sources from them, or that listening in noisy, complex settings is tenuous.

Hearing instruments are designed to amplify sounds to audible levels for individuals with hearing loss. Modern technological advances in hearing instrument technology include directionality, which improves the signal-to-noise ratio; noise reduction, which allows for listening comfort in noise; and wide-range dynamic compression, which is important for ensuring soft sounds are audible and loud sounds do not reach uncomfortable levels. However, these worthy features do not typically maintain the natural localization abilities of the unaided ear, and spatial hearing may be adversely affected in the process.

To restore the natural localization abilities of the unaided ear, ReSound employs split-band directionality through Surround Sound processing, as well as strategic microphone location. Behind-the-ear (BTE) hearing instruments in the Alera product family take advantage of split-band directionality, while Custom Remote Microphone hearing instruments improve localization abilities through placement of the microphone in the upper concha, or concha cymba, of the ear.

In split-band directionality, low frequencies are processed with an omnidirectional response and high frequencies are processed with a directional response. Omnidirectional processing of low-frequency information eliminates the group delay that occurs with directional processing, and thereby may preserve the low-frequency phase characteristics important for spatial localization. In addition, low-frequency gains are maintained as there is no influence of directionality in this frequency region. In contrast, traditional directionality applies directional processing to all frequencies. However, the directional processing delay in the low frequencies can distort interaural time differences of sounds reaching the ears, conceivably making spatial localization more difficult. Further, low-frequency time cues may not be sufficiently audible due to incomplete or inadequate low-frequency gain equalization. By using split-band directionality in BTE hearing instruments, localization cues in the low-frequencies are maintained to promote better spatial hearing.

Custom Remote Microphone hearing instruments consist of a shell that is inserted in the ear, attached to an omnidirectional microphone that is placed in the concha cymba of the ear (Figure 1). Microphone placement has been found to affect the signal-to-noise ratio (SNR), localization ability and spatial awareness (Dillon, 2001). A microphone location within the pinna allows for the natural localization and directional cues afforded by the pinna to be utilized by the listener. Since the external ear serves to collect sounds to enhance localization abilities, placing the microphone within the external ear capitalizes on these advantages.

***FIGURE 1.*** *The Custom Remote Microphone Alera hearing instrument in the ear*.

The benefits of split-band directionality for BTE hearing instruments and of strategic microphone placement for Custom Remote Microphone hearing instruments allow users of Alera hearing aids to enjoy more natural localization abilities. This paper describes how spatial hearing is affected by amplification, and provides support for the use of split-band directionality for better spatial hearing via the results of a study conducted at the University of Leuven, Belgium.

## *The effect of amplification on localization abilities*

In determining the location of sounds in the acoustic environment, the brain processes auditory inputs from both ears. Sounds from each ear are compared to determine the spatial placement and distance from the individual. Two primary auditory cues are known to be important for the correct assignment of sound source location: interaural level differences (ILDs) and interaural time differences (ITDs). The impact of each of these cues is frequency-specific, due to differences in wavelength for high- and low-frequency sounds. ILDs have the greatest impact for high-frequencies, since level differences occur as a sound attempts to cross from one side of the head to the other. Conversely, ITDs have the greatest impact for low-frequencies due to the time and phase differences that occur as long-wavelength low-frequency sounds pass around the head. In addition to ILD and ITD cues, the brain processes information from spectral shaping of sound by the outer ear, head and upper torso to determine the location of sound sources. In general, ILDs and ITDs are dominant in localization in the horizontal plane, which includes azimuth or right-left assignment of sound sources, and spectral cues are most important for the vertical plane, which includes front-back localization.

Hearing instruments, by virtue of the complex signal processing, can affect both interaural difference cues as well as spectral shaping due to the physical characteristics of the external ear and head. For binaural fittings, differences in signal processing between the hearing instruments can distort ITD cues. A prime example of signal processing that can affect ITDs is directionality, which introduces a group delay that can distort phase characteristics for sounds primarily in the low frequencies. Similarly, ILDs may be distorted by compression, which is widely used in amplification to achieve the goals of making soft sounds audible without causing loud sounds to be intolerable. Spectral shaping that occurs for the unaided ear is also altered by the use of hearing instruments, especially for those which place the microphone behind the ear. BTE hearing instruments lose the benefits provided by the pinna and other external ear landmarks as the microphone is moved farther away from the tympanic membrane and ear canal. Figure 2 shows how spectral information is reduced by microphone placement in an omnidirectional BTE relative to the open ear canal (Groth and Laureyns, submitted). Intensity differences for sound sources at 30° and 150° were measured with respect to the nearest ear, and plotted on a frequency scale with blue indicating small differences and red indicating large differences. Large differences in intensity up to 10 dB were observed for the 4000-6000 Hz region for the open ear. Nearly no difference in intensity was observed for the BTE across the frequency range, indicating that these level difference cues are absent when the microphone is placed behind the pinna.

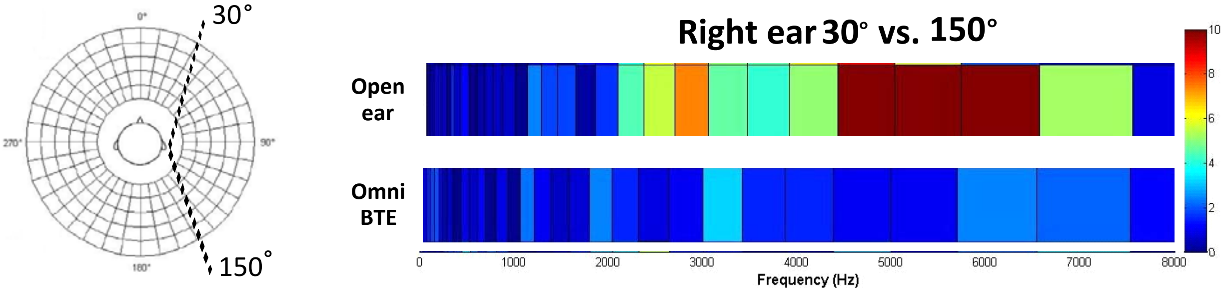


***FIGURE 2.*** *Intensity differences for broadband sound presented from front (30°) and back (150°) for an open KEMAR ear and for an omnidirectional BTE on the ear.*

When compared to omnidirectional processing, directionality in hearing instruments can provide improved localization abilities for both BTE (Keidser et al, 2006) and ITE (Chung et al, 2008) microphone placements. However, the distortions introduced by compression and group delay in conventional directionality schemes remain, degrading the ability of the listener to localize to sound sources as well as the unaided listener.

## *Restoring open ear advantages for localization to the hearing instrument user*

Clearly, the unaided ear provides optimal localization abilities, both through interaural difference cues and through spectral shaping provided in part by the external ear. Thus, to achieve similar advantages for localization, it is prudent to design hearing instrument amplification to model the open ear as closely as possible. For BTE hearing instruments with directionality, ReSound incorporates split-band directionality through Surround Sound processing. For in-the-ear (ITE) devices such as Custom Remote Microphone hearing instruments, strategic microphone location within the concha cymba affords spectral shaping benefits from the pinna.

Conventional directionality applies directional processing across the frequency range. Due to the group delay inherent in directional processing that allows it to amplify sounds from the front more than sounds from the rear, conventional directionality results in distortion and reduced audibility of ITD cues. Split-band directionality processes the high frequencies with a directional response and the low frequencies with an omnidirectional response. Figure 3 shows the directivity index as a function of frequency for a split-band directional and an omnidirectional response. The crossover frequency, or the frequency below which the response is omnidirectional and above which the response is directional, is calculated through the fitting software and based on the individual's hearing thresholds at 250 and 500 Hz, and on the form factor fitted. This calculation ensures audibility is achieved and the signal-to-noise ratio advantages of directionality are maintained for the hearing instrument user. By processing low frequencies with an omnidirectional response, group delay arising from directional processing is eliminated and ITD cues are more fully preserved.

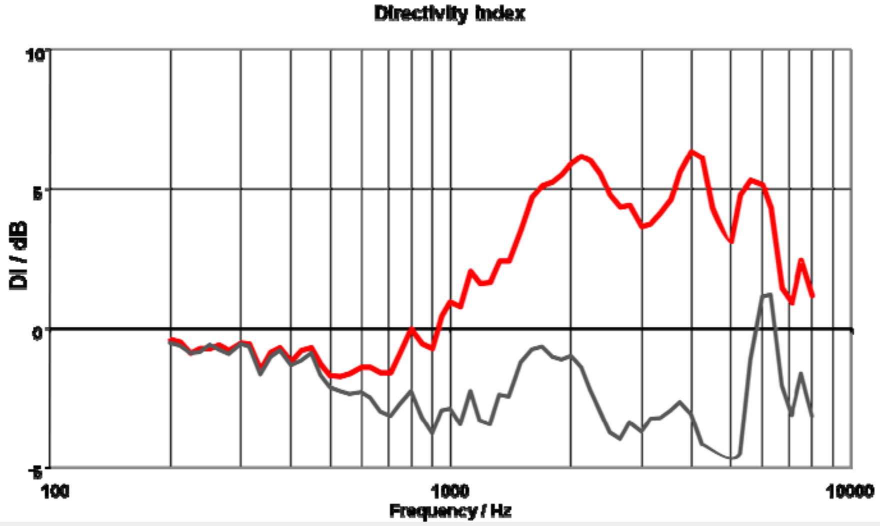
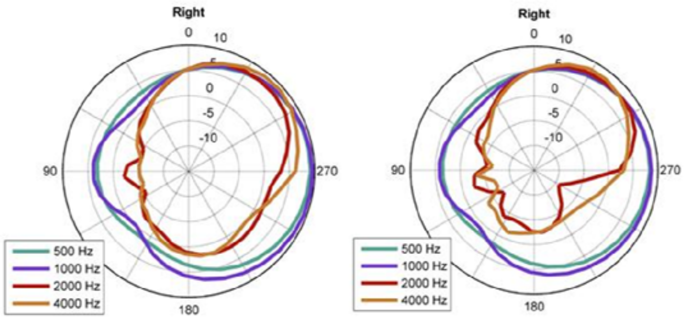


***FIGURE 3.*** *Directivity index plotted for a BTE in Omnidirectional (black curve) and Split-Band Directionality with a fixed hypercardioid response (red curve).*

Split-band directionality mimics the open ear in terms of its spatial directivity patterns. Figure 4 shows the similarities in directivity polar plots for low and high frequencies between split-band directional processing and the open ear. High frequencies are amplified more to the front, showing a directional response while low frequencies are unaffected by the location of the sound source, indicating an omnidirectional response.



•Open human ear

•Surround Sound Processor

***FIGURE 4.*** *Directionality polar plots for the open ear and for split-band directionality (Surround Sound Processor) patterns for four frequencies, as measured on the right ear of KEMAR. Low frequencies have omnidirectional responses, while high frequencies display patterns that are more directional.*

Limiting directionality to the high frequencies has several advantages. High-frequency directionality has been found to be of greater importance than low-frequency directionality when visual or speech-reading cues are absent (Grant & Walden, 1996; Grant, 2005; Grant et al, 2007). Hearing instrument users tend to accept split-band directionality as a means to improved hearing in noise (Stender and Rosenstrauch, 2010; O'Brien et al, 2010). Split-band directionality was determined to be preferable in terms of sound quality as compared to conventional directionality (Groth et al, 2010). This may be due in part to the elimination of bass boost noise, since low frequencies are processed as omnidirectional in split-band directionality. In addition, the improvement in localization abilities may allow listeners to improve speech understanding, since they are more aware of the direction or location in which they should be focusing their attention (Arbogast et al, 2005).

Further support of the use of split-band directionality to preserve localization abilities is provided from a recent study conducted at the University of Leuven (Groth and Laureyns, submitted). The study compared left-right and front-back localization performance of hearing-impaired subjects in three conditions: unaided (with an amplified stimulus to control for audibility factors across conditions), split-band directionality as provided by the Surround Sound processor, and an omnidirectional response. The split-band directionality condition had a crossover frequency of 900 Hz, and the aids were programmed with a fixed hypercardioid response.

In the left-right localization task, subjects were asked to determine the source of the sound in a horizontal array from 90° to the right and 90° to the left while keeping their head fixed directly forward. Multitalker babble was presented at -90° and 90° as well. For the front-back task, subjects sat with their right ear facing the horizontal array. The multitalker babble was again presented at -90° and 90°. Figures 5 and 6 show the set-up for the left-right and front-back tasks, respectively.

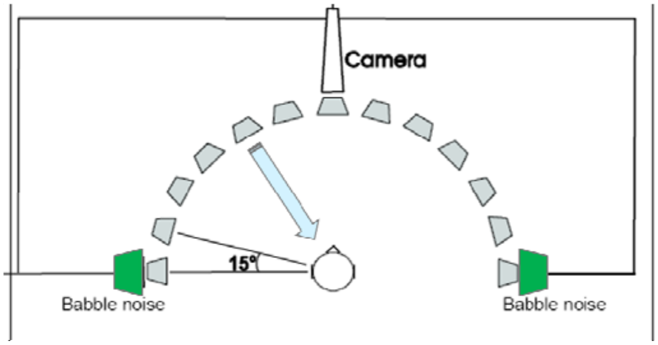


***FIGURE5.*** *Set-up for the left-right localization task.*

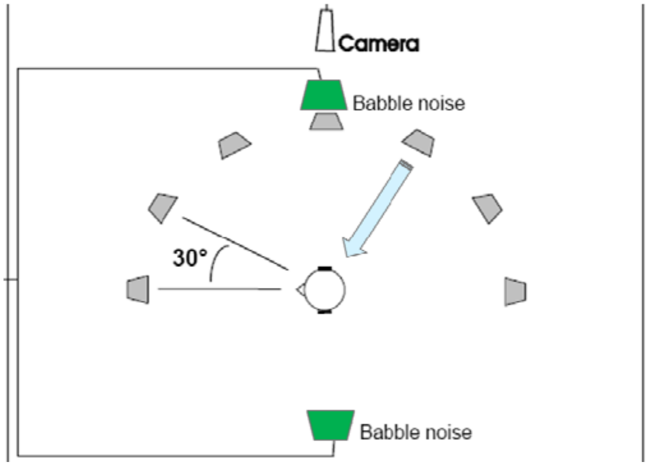


***FIGURE 6.*** *Set-up for the front-back localization task.*

Results were quantified in terms of root-mean-square (RMS) error in degrees for the left-right task, and in terms of the percentage of front-back confusions for the front-back task. No significant differences were shown for the left-right localization task for any of the hearing instrument conditions with respect to the unaided condition. This was an expected result, since the ITDs were maintained and audibility was equivalent due to omnidirectional processing in the low frequencies for both the split-band and omnidirectional conditions. Figure 7 shows the results for left-right localization.

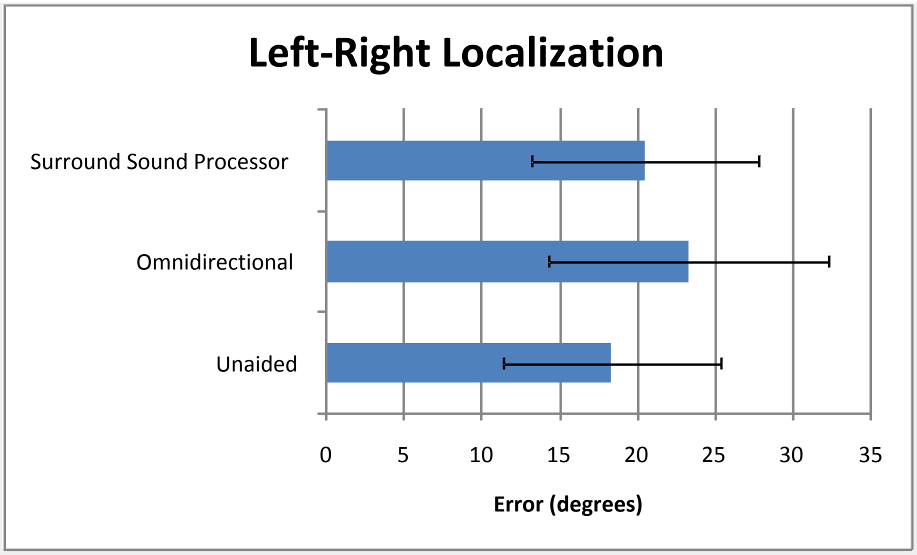


***FIGURE 7.*** *Results for the left-right localization task; no significant differences were observed across conditions.*

For the front-back localization task, similar results were revealed for the unaided and split-band directional conditions. A significantly greater degree of errors was observed for the omnidirectional condition than for either the unaided or the split-band directionality condition. This is consistent with results reported elsewhere (Keidser et al, 2009), which indicated better front-back localization performance when directionality is limited to the high frequencies as compared to omnidirectional processing. Figure 8 illustrates these front-back localization task results.

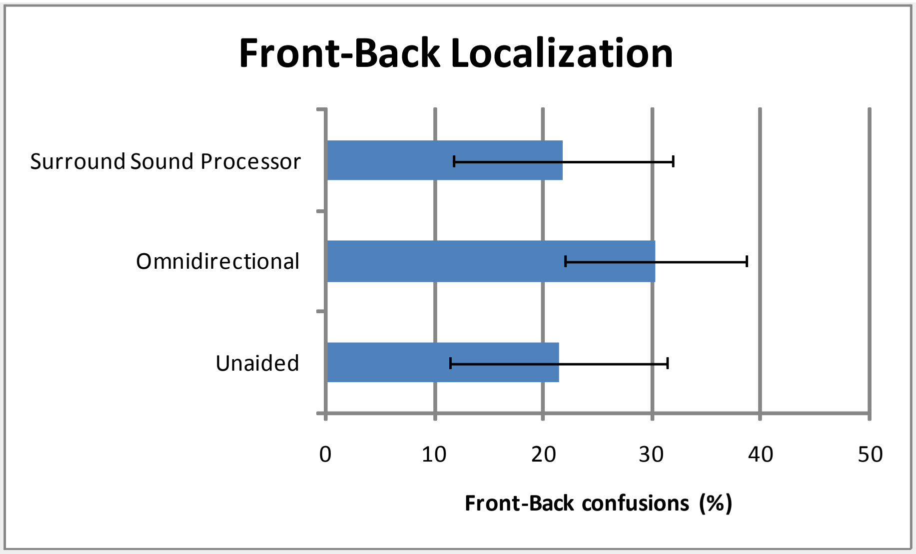


***FIGURE 8.*** *Front-back localization task results, indicating a greater degree of errors for the omnidirectional condition than the other conditions.*

The Groth and Laureyns study (2010) shows the advantages of split-band directionality provided through the Surround Sound processor for localization abilities, specifically in terms of front-back localization. In addition, ReSound products programmed with Natural Directionality II were designed to further enhance spatial hearing abilities by providing greater spatial awareness by virtue of having one ear fitted with an omnidirectional response while the other ear is fitted with a split-band directional response. Lab results with asymmetric directional fittings result in comparable directional benefit to binaural directional fitting (Bentler et al., 2004, Cord et al., 2007, Mackenzie and Lutman, 2005) and improved ease of listening as compared to binaural directional fitting (Cord et al, 2007), while at the same time providing split-band directionality advantages for localization abilities.

Custom Remote Microphone hearing instruments, due to their design, place an omnidirectional microphone in the upper concha of the ear. Since the microphone is omnidirectional there is no need to overcome obstacles to localization due to directionality. In addition, the unique microphone placement allows natural localization cues and better SNR effects afforded by the pinna (Griffing and Preves, 1976) to occur. In support of this, hearing-impaired listeners were found to perform better in a localization task when wearing ITEs than with BTEs (Westermann and Toepholm, 1985). Further, Picanali et al (2008) demonstrated a high-frequency advantage for the remote microphone placement compared to BTE microphone placement for the 3500-5000 Hz frequency region. Van den Bogaert et al (2008, 2009) also studied the effects of the remote microphone placement on localization abilities. Front-back confusions were significantly reduced as compared to a directional BTE, indicating better localization abilities. This was to be expected, due to the better maintenance of the spectral cues afforded by the external ear when the microphone is placed in the concha cymba. All of these results point to listeners' better use of pinna effects for high-frequency directivity cues, and, by extension, better localization abilities when the microphone is strategically placed in the ear.

## *Summary*

Signal processing in hearing aids can be detrimental to the natural localization abilities enjoyed by unaided listeners. Distortions of phase and level cues can occur, as well as spectral shaping changes due to suboptimal microphone placement, especially for BTE hearing instruments. To attempt to restore the natural localization abilities lost due to these factors in directional BTEs, ReSound's Surround Sound processor incorporates split-band directionality. Since only high frequencies are processed as directional in split-band directionality, horizontal localization abilities are preserved through low-frequency ITD cues and front-back localization cues are maintained relative to the open ear. For Custom Remote Microphone hearing instruments, the advantageous placement of the microphone in the concha cymba permits the individual to benefit from high-frequency pinna effects that enhance front-back localization abilities. Thus, the ReSound Alera product family, including BTEs and Custom Remote Microphone hearing instruments, provides technology to promote more natural localization abilities for the listener.

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