Proven benefits of ReSound Binaural Directionality™

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Abstract

Binaural Directionality is a directional signal processing strategy that was introduced with the launch of ReSound Verso 9 hearing instruments. As a component of Binaural Fusion technology, it capitalizes on the synergistic relationship between auditory processing in the brain and sensory inputs from both ears. Binaural Directionality provides the brain with the auditory information it requires from both ears to make informed decisions about the listening environment, through a selection of four binaural microphone responses. The assignment of omnidirectional processing for the low frequencies and directional processing for the high frequencies adds another layer of sophistication to the processing, resulting in a more natural response that can be utilized by the brain. Two studies provided evidence of the effectiveness of Binaural Directionality to increase the signal-to-noise ratio and to provide excellent, natural sound quality for directional signal processing.

One of the biggest leaps in technology in 2012 was the introduction of device-to-device communication using 2.4 GHz wireless technology in hearing instruments. For the first time, sound signals could be sent via 2.4 GHz radio frequency transmission between paired hearing instruments, giving rise to new binaural features such as Binaural Directionality. ReSound went one step further than just providing device-to-device coordination; it applied this technology to provide true user benefit for speech understanding in complex and changing environments.

Contributing to the Surround Sound by ReSound experience, Binaural Directionality was designed to elegantly and comprehensively incorporate the findings of published research in the areas of user microphone mode preferences, signal-to-noise ratio optimization, and frequency-specific directionality, to achieve optimal results. In addition, two studies provide further evidence about the effectiveness and benefits of Binaural Directionality, as implemented in ReSound Verso hearing instruments.

Evidence-based development of Binaural Directionality

Binaural Directionality is an innovative approach to directional signal processing that incorporates inputs from both ears to determine the location and level of acoustic inputs. Via device-to-device communication, the most advantageous binaural microphone response is applied for each ear. As an integral component of ReSound's Binaural Fusion technology, Binaural Directionality strives to present the most optimal sound representation for the brain. Thus, as the listening environment changes, the binaural microphone response may also change. This occurs to provide the brain with the most complete picture of the auditory scene, to enable higher auditory functions such as the choice to attend to certain sound sources.

In Binaural Directionality, an omnidirectional or fixed directional pattern is automatically assigned for each ear to create the best possible directional response for speech while maintaining sound awareness for other sound inputs which may be of interest. This unique approach to directionality allows users to decide what to attune to – even if it results in turning towards a different, more salient sound source which may not be directly in front of them. Unlike other beam-switching directional features that offer high directional benefit to a sound source in a non-look direction, Binaural Directionality offers a more comprehensive picture of the acoustic environment, and does not force the listener to attend to a single sound or speech source. In other words, the user is in the driver's seat, and can choose to pay attention to or ignore a multitude of sounds in the listening environment.

Amid a marketplace rife with competing options in inter-device communication, ReSound's Binaural Directionality was the first to introduce a truly binaural strategy that takes advantage of scientifically proven better-ear listening strategies, interaural phase differences and auditory spatial attention strategies.[1-5]

Binaural Directionality provides the brain with the sensory information it requires from both ears to make informed decisions about the listening environment. To achieve this, four binaural directional responses are offered. The development of this strategy was based on empirical data, indicating which binaural microphone configurations would be optimal or preferred by users in a variety of sound environments. The end goal was to provide the user with a better signal-to-noise ratio in noise while maintaining the purest sound quality for quiet environments. Table 1 shows the four possible configurations, and the rationale for when these binaural responses would be most advantageously applied.

Right Hearing Instrument Mode	Left Hearing Instrument Mode	Rationale and Support from the Literature
Omnidirectional	Omnidirectional	Users strongly prefer a bilateral omnidirectional response in quiet environments.[6,7]
Directional	Directional	Provides the greatest benefit when the speech signal is predominantly in front of the listener.[8]
Omnidirectional Directional	Directional Omnidirectional	Asymmetric directionality improves ease of listening and awareness of surroundings as compared to bilateral fixed directional fittings,[9] without significantly degrading directional benefit.[9-11] In a noisy environment with speech to one side of the listener, the best intelligibility is achieved if there is an omnidirectional response for the speech side and a directional response for the opposite side.[12-14]

Table 1. Published research findings on optimal binaural microphone response patterns influenced the development of the four binaural microphone responses of Binaural Directionality.

Achieving a more natural response through Directional Mix processing

As with every directional option in the Surround Sound Processor, Binaural Directionality incorporates Directional Mix Processing. This is a bandsplit directionality strategy, in which low frequencies are processed as omnidirectional and high frequencies are processed as directional. The benefits of this differential, frequency-specific processing are twofold.

First, processing low frequencies in an omnidirectional pattern recreates a more natural sound quality, improves environmental awareness, and aids in the ability to localize sounds in the environment. These advantages are due to the dissimilar behavior of low and high frequency sounds as they arrive at and pass around the head. Low frequencies, characterized by long wavelengths, maintain their energy as they diffuse around the listener's head. As the frequency decreases, diffraction of the sound around the head also decreases. Thus, the unaided, open ear response for low frequencies arriving from one side of the head is very similar to an omnidirectional response. As a slight phase difference is perceptible for low-frequency sounds reaching each ear, people naturally use these differences as important cues for sound source localization.

High frequencies, by virtue of their shorter wavelengths, are more affected by head shadow effects as they pass around the head. This naturally creates a more directional response for high frequencies, as their energy is decreased at one ear as compared to the other. Use of bandsplit directionality thereby preserves the natural behaviors of low and high frequencies as they arrive at each ear (Figure 1), and has been shown to improve front/back localization abilities as compared to unaided and aided listening with omnidirectional or full-spectrum directional processing.[15]

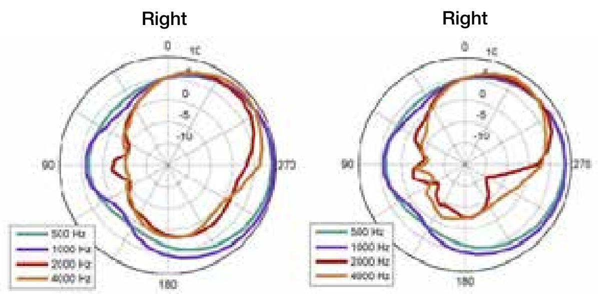


Figure 1. Left panel: Open ear response per frequency; Right panel: ReSound Directional Mix Processor response per frequency.

The second benefit of bandsplit directionality is the alleviation of a problem inherent in directional processing: the roll-off of low-frequency amplification. This decrease in gain occurs due to the similarity in phase relationships of low frequency sounds as they arrive at the front and rear microphones. To overcome this decreased audibility, equalization or a "bass boost" is typically applied. However, this artificial boost in gain may result in an audible noise floor,[16] especially for listeners with better hearing in the low frequencies. Omnidirectional processing for the low frequencies restores audibility without introducing this increase in the noise floor. In addition, omnidirectional processing helps to prevent over-amplification of low-frequency near-field signal distortions, such as wind noise created from the distinct air vortexes at each microphone.[17-23]

ReSound's Directional Mix Processor automatically calculates the crossover frequency between omnidirectional and directional processing, based on the individual's low-frequency hearing thresholds and the specific hearing instrument model. A low Directional Mix setting means there is less of the signal processed as directional and the crossover frequency is thereby higher; a high Directional Mix setting indicates more of the signal is processed as directional and the crossover frequency is subsequently lower. This setting may also be changed by the hearing professional if necessary through Aventa fitting software.

Evidence supporting Binaural Directionality

The basis for the development of Binaural Directionality was clearly rooted in published literature regarding enhanced sound quality for directional processing, microphone mode preference, optimization of the signal-to-noise ratio (SNR) and speech intelligibility. In addition to this research, more evidence has been gathered to further support the performance of Binaural Directionality as implemented in ReSound Verso 9 devices.

Two studies were conducted:

- Study #1: To verify the effects of frequency-specific directionality on speech intelligibility and sound quality
- Study #2: To investigate if speech intelligibility improvements are provided by Binaural Directionality compared to a traditional, fixed asymmetric directional response.

Study #1: Investigation of the effect of Directional Mix on speech intelligibility and sound quality

This study had three objectives:

1. To observe improvements in speech intelligibility in noise performance obtained through bandsplit directionality compared to omnidirectional processing;
2. To investigate if changing the Directional Mix setting has a significant impact on speech intelligibility in noise;
3. To determine if a difference in sound quality is perceived for bandsplit directionality with different settings of Directional Mix as compared to an omnidirectional setting.

ReSound Alera 977-DVIW behind-the-ear (BTE) hearing instruments were used in this study; however, as no change to bandsplit directionality was implemented for ReSound Verso devices as compared to Alera devices, these results apply directly to the implementation of the Directional Mix Processor in Verso.

Methods

Twenty subjects completed this investigation. Ten subjects were fitted with Alera 977-DVIW open (thin tube) BTEs, and ten were fitted with Alera 977-DVIW closed BTEs. Subjects were assigned to each fitting group based on the severity of their low-frequency hearing thresholds; individuals in the open fitting group had mild sloping to moderately-severe sensorineural hearing losses, while individuals in the closed fitting group had moderate sloping to severe sensorineural hearing losses.

Two hearing instrument programs were established for each subject: one with an omnidirectional response and the other with a fixed (hypercardioid) directional response. Aside from DFS Ultra (calibrated and set to "mild"), all other features were deactivated. Gains were programmed according to the ReSound proprietary Audiogram+ targets at "Experienced-Nonlinear" settings through Aventa 3.3 fitting software, and adjusted if necessary, according to the user's preference. However, gains were programmed identically between the omnidirectional and directional programs for each subject, and were verified to be equivalent through real-ear insertion gain measurements.

Speech intelligibility in noise performance was assessed through the Dantale II test.[24] This adaptive test is comprised of five-word sentences, presented in a background of speech-shaped noise at 65 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. Subjects completed three sentence lists for each of five test conditions: omnidirectional, and fixed directionality with "high," "medium," "low" and "very low" Directional Mix settings. The testing order of conditions and the sentence lists were counterbalanced across subjects.

To assess sound quality for bandsplit directional and omnidirectional processing, subjects completed two-alternative forced choice comparisons of "noisiness." Three conditions were presented, as outlined in Table 2. While seated in a quiet sound booth, subjects were asked to choose which microphone response had the highest degree of noise in each condition. Condition order was counterbalanced across subjects.

Condition	Forced Choice Comparison
1	Omnidirectional vs. Fixed Directional (High Directional Mix)
2	Omnidirectional vs. Fixed Directional (Very Low Directional Mix)
3	Fixed Directional (High Directional Mix) vs. Fixed Directional (Very Low Directional Mix)

Table 2. Conditions tested for sound quality comparisons re: noisiness.

Results and discussion

Real-ear insertion gain

No significant difference ($p < 0.01$) in real-ear insertion gain measures was revealed between the omnidirectional program and the directional program with a high Directional Mix setting (which provides a directional response across the greatest proportion of the overall frequency spectrum). Figure 2 illustrates the equivalence of gain settings between programs. These results indicate that bandsplit directionality as implemented in ReSound hearing instruments equalizes low frequency gain adequately with respect to the omnidirectional response. Further, the equivalency of real-ear insertion gain measures suggests that audibility was not a factor in the speech intelligibility or the sound quality results.

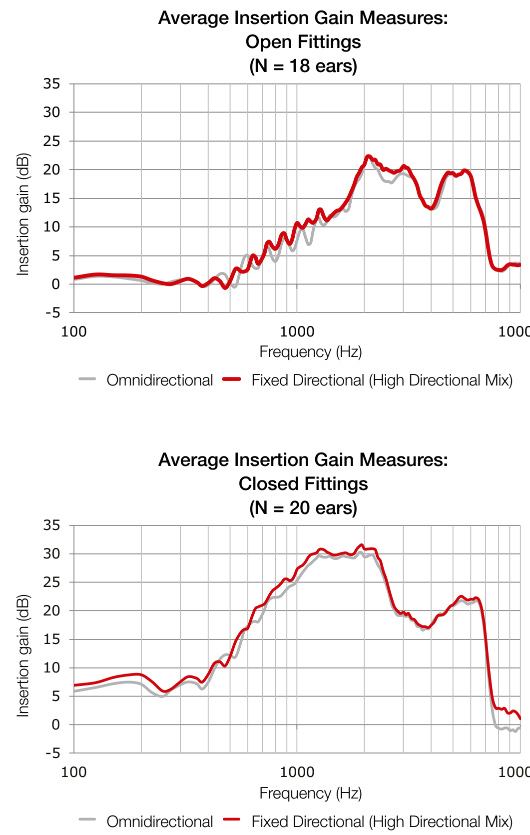
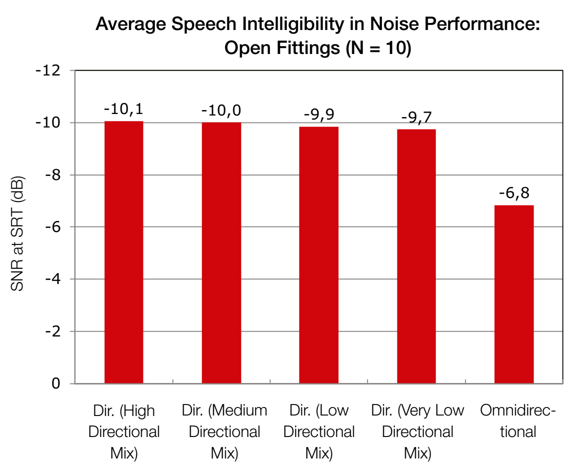


Figure 2. Average insertion gain measures for open and closed fittings revealed no significant differences between omnidirectional and directional program gains.

Speech intelligibility in noise

The results of the speech intelligibility in noise testing for both the open and the closed fitting groups revealed significantly better performance for every directional condition as compared to the omnidirectional setting ($p < 0.01$). This indicates that regardless of the Directional Mix setting, significantly better SNR scores were obtained for directional processing as compared to omnidirectional processing (Figure 3).



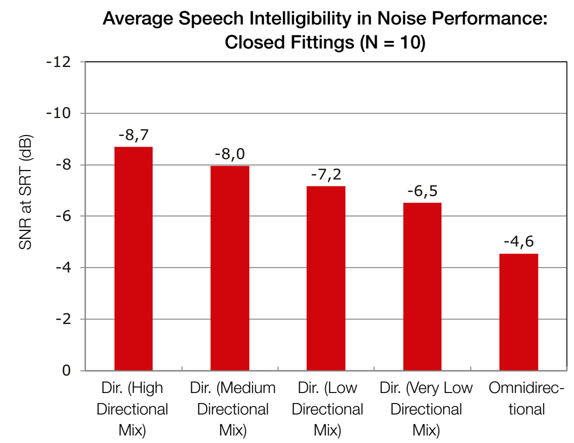


Figure 3. Speech intelligibility in noise results for the open and closed fitting groups.

Results for the open fitting group indicated an average directional benefit of about 3 dB for the directional response with a high Directional Mix setting, as compared to the omnidirectional condition. Among the Directional Mix settings for this group, no significant differences in SNR score were revealed. However, this is in accordance with other findings that describe limited directional benefit for open hearing instruments, due to the typical audibility of unamplified low-frequency sounds entering the ear.[25,26]

For the closed fitting group, it was observed that as the Directional Mix setting increased for the directional conditions, the directional benefit also significantly increased ($p < 0.01$). An average 4-dB SNR benefit was revealed for the directional condition with a high Directional Mix setting, as compared to the omnidirectional setting. This indicates that as more of the frequency range is directionally processed, the SNR benefit increases.

Sound quality

No significant difference in sound quality was observed among any of the omnidirectional or directional conditions, for either the open or closed fitting groups. This is consistent with the results of a study by Groth et al.,[27] in which listener preference was the same for both bandsplit directional and omnidirectional processing. These results, in conjunction with the equivalency of insertion gains for omnidirectional and directional processing, indicate that ReSound's Directional Mix Processor achieves the goal of restoring low-frequency audibility without adding perceptible noise, thereby preserving sound quality for directional processing.[28]

Study #2: Investigation of speech intelligibility improvements provided by Binaural Directionality as compared to standard asymmetric directionality

The purpose of this study was to investigate if the microphone response optimizations afforded by device-to-device communication in Binaural Directionality result in improved speech intelligibility when compared to standard asymmetric directionality, which does not utilize inter-device communication.

Methods

Twenty subjects with normal hearing and nineteen subjects with symmetric, sloping mild-to-moderate sensorineural hearing losses participated in this experiment. All subjects were fitted with ReSound Verso 977-DW BTE hearing instruments and closed Comply earmolds for each ear. Two programs were provided: one set to Binaural Directionality and the other set to asymmetric directionality. The asymmetric directionality tested in this study provided a constant, fixed directional response for the right ear, and assigned an omnidirectional response for the left ear. A right-ear advantage was assumed, in the absence of asymmetrical hearing thresholds among subjects.[29]

Each program was set to the "high" Directional Mix setting, to provide the greatest degree of directionality across the frequency response. All other features were deactivated in each program. Normal-hearing subjects were fitted with 10 dB flat linear gains, while subjects with hearing losses were fitted with Audiogram+ gains prescribed for their hearing losses at "Experienced-Nonlinear" user settings.

Participants' performance with Binaural Directionality and standard asymmetric directionality was evaluated for two acoustic environments (Figure 4). In the first environment, speech was presented in front of the listener and noise was presented from behind. In the second environment, speech was presented on the right side of the listener and noise was presented on the left. These environments were chosen as they represent two listening situations in which Binaural Directionality adjusts the binaural response to optimize speech recognition. In acoustic environments such as these, fixed asymmetric directionality with the right ear configured as directional may not provide the optimal signal-to-noise ratio benefit in comparison to a bilateral directional setting,[8] or in comparison to an asymmetric directional setting with the ear nearest the speech configured as omnidirectional.[12-14] In contrast, Binaural Directionality has the ability to optimize each microphone configuration via device-to-device communication and real-time analysis of the acoustic environment.

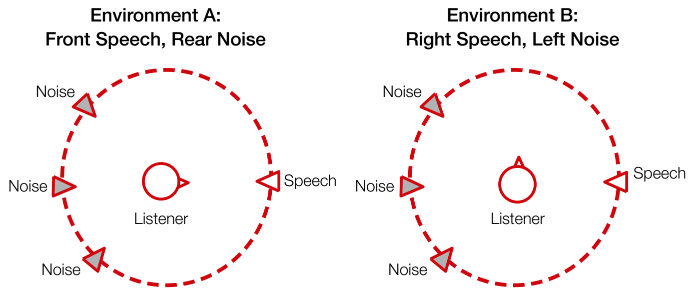


Figure 4. Speech in noise environments.

As with the bandsplit directionality study, the Dantale II sentence-in-noise test was administered to subjects. Test subjects were seated in a sound-treated booth with loudspeakers arranged as Environment A or Environment B. Each subject completed three sentence lists (30 sentences) of the Dantale II test for each condition in each acoustic environment, for a total of four tests per subject. The order of the test conditions as well as the sentence lists were randomized across subjects.

Results and discussion

Results for each noise environment and subject group were analyzed separately and then collectively. Single and double-factor repeated measure ANOVA comparisons were conducted, and Bonferroni adjustments were used to compensate for multiple comparisons. Results for subjects in the normal hearing group indicated significantly better performance for Binaural Directionality as compared to standard asymmetric directionality in both Environments A and B ($p < 0.01$, for each environment). Similar results were obtained for the group of subjects with hearing loss, with Binaural Directionality providing significantly better speech intelligibility performance in noise as compared to standard asymmetric directionality ($p < 0.05$, for each environment). In addition, significant improvement in SNR scores was revealed for each environment when all subject data was pooled and analyzed ($p < 0.01$). Figure 5 illustrates the results for each subject group, while Figure 6 shows the results for all subjects.

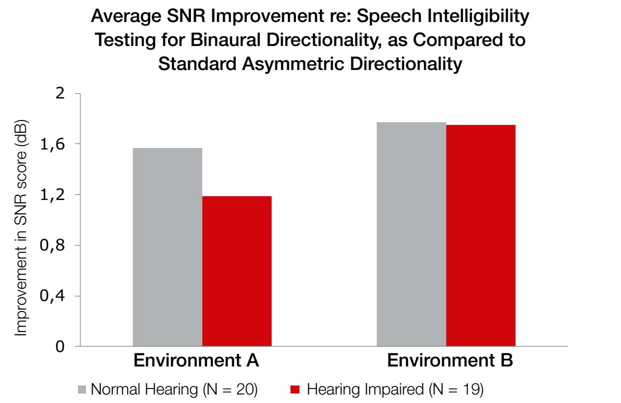


Figure 5. Results of speech intelligibility in noise testing revealed significantly better performance for Binaural Directionality for each group in each environment.

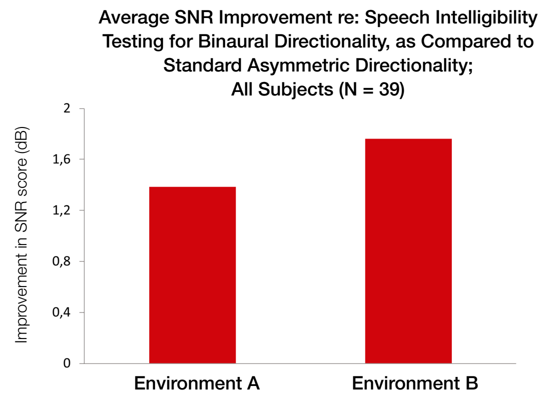


Figure 6. Speech Intelligibility testing results for all subjects revealed significantly better performance for Binaural Directionality as compared to standard asymmetric directionality in both environments.

This study revealed improved SNR scores for the Binaural Directionality condition, which is analogous to improved speech recognition, as compared to traditional asymmetric directionality. With all characteristics of the two conditions identical except for the ability of Binaural Directionality to adapt to the listening environment, it was determined that this optimization in binaural microphone response had a direct impact in the observed improvement in speech intelligibility performance in noise.

Conclusions

Binaural Directionality is a multi-faceted, highly sophisticated signal processing strategy that achieves several goals. First, its incorporation of the Directional Mix Processor restores audibility for directionally-processed low-frequency sounds, without sacrificing sound quality. Users tend to perceive no difference in the sound quality of omnidirectional processing and ReSound's unique implementation of bandsplit directional processing. Yet listeners still enjoy significant directional benefit with ReSound's Directional Mix Processor as compared to omnidirectional signal processing in noisy environments, regardless of the Directional Mix setting. In sum, the Directional Mix Processor offers all the benefits of traditional directional processing without its typical costs to the overall sound quality.

Second, Binaural Directionality provides SNR benefit while allowing the user to remain present in the acoustic surroundings. As "life often happens when you're not looking," Binaural Directionality does not cut the listener out of potentially important acoustic information arising from one or multiple non-look directions.

Finally, the flexibility in binaural microphone response provided by Binaural Directionality results in a greater degree of directional benefit than traditional asymmetric directionality for certain difficult listening environments. Through its ability to correctly classify the environment and transmit information between paired devices, it applies the appropriate binaural microphone response for the listening situation – whether it is bilateral omnidirectional, bilateral directional, or asymmetric directional to either side. Thus, Binaural Directionality is an all-encompassing directional feature, giving users the freedom to enjoy seamless hearing in complex acoustic environments.

References

1. Zurek PM. Binaural advantages and directional effects in speech intelligibility. In G. Studebaker & I. Hochberg (Eds.), Acoustical Factors Affecting Hearing Aid Performance. Boston: College-Hill, 1993.
2. Akeroyd MA. The across frequency independence of equalization of interaural time delay in the equalization cancellation model of binaural unmasking. J Acoust Soc Am. 2004:116;1135–48.
3. Edmonds BA, Culling JF. The spatial unmasking of speech: evidence for within-channel processing of interaural time delay. J Acoust Soc Am. 2005:117;3069–78.
4. Shinn-Cunningham B, Ihlefeld A, Satyavarta, Larson E. Bottom-up and Top-down Influences on Spatial Unmasking. Acta Acustica united with Acustica. 2005:91; 967-79.
5. Simon H, Levitt H. Effect of dual sensory loss on auditory localization: Implications for intervention. Trends Amplif. 2007:11;259-72.
6. Walden B, Surr R, Cord M, Dyrlund O. Predicting hearing aid microphone preference in everyday listening. J Am Acad Audiol. 2004:15;365-96.
7. Walden B, Surr R, Cord M, Grant K, Summers V, Dittberner A. The robustness of hearing aid microphone preferences in everyday environments. J Am Acad Audiol. 2007:18;358-79.
8. Hornsby B. Effects of noise configuration and noise type on binaural benefit with asymmetric directional fittings. Seminar presented at: 155th Meeting of the Acoustical Society of America; June 30-July 4, 2008; Paris, France.
9. Cord MT, Walden BE, Surr RK, Dittberner AB. Field evaluation of an asymmetric directional microphone fitting. J Am Acad Audiol. 2007:18;245-56.
10. Bentler RA, Egge JLM, Tubbs JL, Dittberner AB, Flamme GA. Quantification of directional benefit across different polar response patterns. J Am Acad Audiol. 2004:15;649-59.
11. Kim JS, Bryan M. The effects of asymmetric directional microphone fittings on acceptance of background noise. Int J Audiol. 2011:50(5);290-296.
12. Hornsby B, Ricketts T. Effects of noise source configuration on directional benefit using symmetric and asymmetric directional hearing aid fittings. Ear Hear. 2007:28;177-86.
13. Coughlin M, Hallenbeck S, Whitmer W, Dittberner A, Bondy J. Directional benefit and signal-of-interest location. Seminar presented at: American Academy of Audiology Convention; 2008; Charlotte, NC.
14. Cord MT, Surr RK, Walden BE, Dittberner AB. Ear asymmetries and asymmetric directional microphone hearing aid fittings. Am J Audiol. 2011:20;111-122.
15. Keidser G, O'Brien A, Hain JU, McLelland M, Yeend I.The effect of frequency-dependent microphone directionality on horizontal localization performance in hearing-aid users. Int J Audiol. 2009:48;789-803.

16. Ricketts T, Henry P. Low-frequency gain compensation in directional hearing aids. Am J Audiol. 2002:11(1);29-41.

17. Thompson SC. Directional microphone patterns: They also have disadvantages. Audiology Online, 2000.

18. Kates J. Digital Hearing Aids. San Diego: Plural Publishing, 2008.

19. Beard J, Nepomuceno H. Wind noise levels for an ITE hearing aid. Knowles Engineering Report, 128, Revision A, 2001.

20. Thompson S, Dillon H. Wind noise in hearing aids. Seminar presented at: American Academy of Audiology Convention, Philadelphia, PA.

21. Chung K, Mongeau L, McKibben N. Wind noise in hearing aids with directional and omnidirectional microphones: polar characteristics of behind-the-ear hearing aids. J Acoust Soc Am. 2009:125(4);2243–59.

22. Chung K, McKibben N, Mongeau L. Wind noise in hearing aids with directional and omnidirectional microphones: polar characteristics of custom-made hearing aids. J Acoust Soc Am. 2010:127(4);2529-42.

23. Larsson P, Olsson P. Detection of wind noise in hearing aids. Masters thesis, Department of Electroscience, Lund Institute of Technology, March, 2004.

24. Wagener K, Josvassen JL, Ardenkjær R. Design, optimization, and evaluation of a Danish sentence test in noise. Int J Audiol. 2003:42;10-17.

25. Magnusson L, Claesson A, Persson M, Tengstrand T. Speech recognition in noise using bilateral open fit hearing aids: the limited benefit of directional microphones and noise reduction. Int J Audiol. 2013:52(1);29-36.

26. Valente M, Mispagel KM. Unaided and aided performance with a directional open-fit hearing aid. Int J Audiol. 2008:47;329-336.

27. Groth J, Laureyns M, Piskosz M. Double-blind study indicates sound quality preference for Surround Sound Processor. Hear Rev. 2010:17(3);273-284.

28. Moeller KN, Jespersen CT. The Effect of Bandsplit Directionality on Speech Recognition and Noise Perception. Hear Rev. 2013: In press.

29. Kimura D. Functional asymmetry of the brain. Cortex 1967: 3;163-178.

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