SILICON MICROPHONE TECHNOLOGY

Advances Multi-Channel Adaptive Directional Systems

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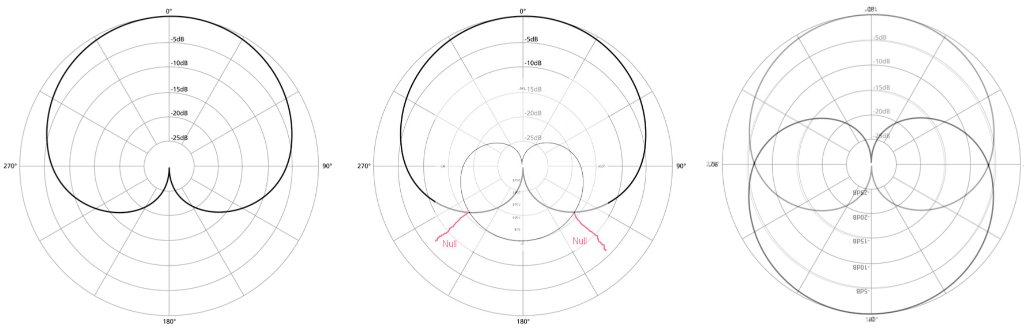


Modern hearing aid technology allows the response pattern of a multi-microphone directional array to be varied in response to the acoustic environment. For example, some systems attempt to identify noise sources and respond by steering an acoustic null or nulls formed by the directional microphones toward the noise source. While this technology holds the promise of improved speech intelligibility and comfort in noise, previous implementations have not consistently translated to real-world benefits (Bentler et al., 2004). This lack of real-world benefit stems in part from microphone "drift" and subsequent microphone mismatch, which negatively affect directional microphone performance. With the introduction of Starkey Hearing Technologies' newest products, microphone drift is minimized, resulting in a multi-microphone directional system that has stable and predictable performance over time. This article provides a tutorial on adaptive directional microphones and their performance characteristics while introducing Starkey Hearing Technologies' solution to the problem of microphone drift. In addition, evidence-based data will demonstrate the benefit of Starkey Hearing Technologies' new multi-channel, adaptive, directional, beam-forming system.

HOW ADAPTIVE DIRECTIONAL SYSTEMS WORK

All directional microphones have two or more ports separated by a known distance on the case of a hearing aid. The simplest directional microphones function via a fixed timing difference between sounds arriving at each microphone port, which funnels acoustic energy to a single microphone diaphragm. The difference in arrival time, or delay, at each of these ports dictates the polar response of the directional system. In systems with a single diaphragm, the polar response is static or fixed; however, in systems with multiple microphones, this delay can be digitally manipulated to modify the polar response. Similar to changing the physical spacing of the ports, applying a digital delay between the microphones in a dual-microphone array facilitates modification of the directivity pattern, and by varying this delay in a multi-channel hearing aid, different directional patterns can be created in different frequency ranges.

Today's directional, or beamforming, microphone arrays function differently across hearing aid manufacturers. For instance, there are differences between what is regarded as a simple adaptive directional array and a fully adaptive directional array, the latter of which is described by Elko and Pong (1995). In a fully adaptive directional system, each hearing aid creates an acoustic estimate of the type and location of sound in the patient's surrounding environment, which is facilitated via the delay characteristics between multiple microphones. Based on this delay, the hearing aid maps the source location of acoustic energy and continuously varies the response such that the response null, or least sensitive portion of the microphone response, is directed toward the dominant noise source. This has the effect of maximally reducing noise around the listener. The response is optimized when the hearing aid performs this function for each hearing aid frequency channel and achieves a microphone response that is continuously varied to minimize noise across the frequency range of the hearing aid. The true advantage of fully adaptive directional systems is that this null can be directed to any off-axis location around the listener. In contrast, more traditional adaptive directional microphones switch discretely between fixed sets of polar responses and may limit the amount of noise suppression if a noise source falls outside the null region. Therefore, a fully adaptive directional system will always perform as least as well, if not better than, a fixed directional system or a directional system that switches discretely between a set of polar responses.

The caveat to a indeterminate fully adaptive directional system is that there is a risk of suppressing sound sources that may be of value to both adults and children (Kuk, Keenan, Lau & Ludvigsen, 2005; Ricketts, Galster & Tharpe, 2007). Starkey Hearing Technologies' new fully adaptive directional system, known as Acuity Directionality™, accounts for this via Speech ID, an off-axis noise tracker and suppressor. Off-axis noise tracking and suppression refers to the ability to direct the null of the response away from meaningful sounds, such as speech in the rear hemisphere, to protect the integrity of the signal in noisy environments. Specifically, as the system works fluidly to maintain indeterminate off-axis noise suppression, a second layer of logic searches for dominant speech in that same location. When a talker is identified to the side or behind the listener, the hearing aid adaptively directs the null away from that talker and directs the sensitive region, or response lobe, of the polar response toward the talker. As the talker moves around a listener, the suppressive null smoothly and continuously steers away from that talker as the response lobe tracks the talker's location. Each of these fully adaptive behaviors, the suppression of off-axis noise and the tracking of off-axis talkers, is accomplished in each hearing aid channel.

THE ENEMY OF DIRECTIONAL PERFORMANCE: "DRIFT"

Conventional electret microphones found in most of today's hearing aids use a polyester diaphragm that is held a few microns away from a metal back plate that holds an electrical charge. When sound hits the suspended diaphragm, it moves toward and away from the metal plate in sympathy with the energy of the sound waves. Because the two surfaces are electrically charged, the movement induces a fluctuating voltage. This change in voltage can be detected, amplified and processed by the hearing aid as the electrical equivalent of the original sound.

The diaphragm and surround are weak links in the electret microphone. Selecting a material for the surround requires a number of compromises including, but not limited to, strength, thickness, flexibility, permeability to water vapor, and compatibility with the adhesives required to connect the components of the microphone together. Even the most well-engineered components are susceptible to moisture, temperature changes and environmental contamination. Over time, these factors cause unpredictable changes in the sensitivity of the electret microphone, a phenomenon known as "drift." Assuming there is no change to the directional inlets in a directional system over time, conventional single-diaphragm directional systems are negligibly affected by drift. However, drift spells dire and negative consequences for directional systems with multiple microphones, which are the very systems that fully adaptive directional arrays depend upon. Out of the factory, the microphones in a multi-microphone directional hearing aid are matched in sensitivity. Over time, drift causes a mismatch in sensitivity across the microphones, which then compromises the directional response of the system. Figure 1 illustrates the effects of a 0.8dB mismatch in microphone sensitivity on the polar response pattern at 500 Hz for a dual microphone directional system. In this example, the blue polar response shows well-defined response nulls that act to suppress noise at roughly 115 degrees and 255 degrees behind the listener. The red

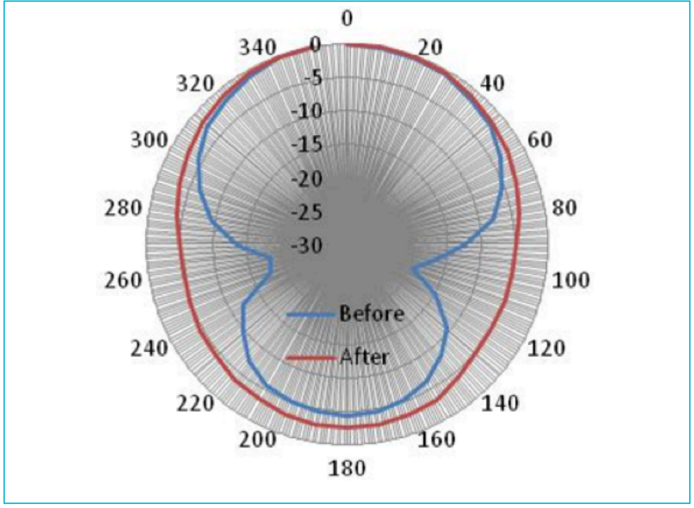
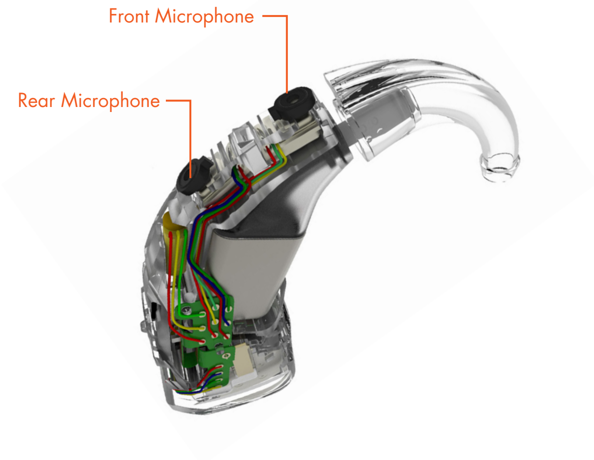


Figure 1: *Effect of a 0.8dB mismatch in microphone sensitivity on the directional response at 500 Hz for a dual-microphone directional array.*



response illustrates the near elimination of those nulls as a result of the sensitivity mismatch between microphones.

The challenge facing clinicians is that microphone mismatch resulting from drift causes hearing aids to remain in a functionally omnidirectional mode at all times, even when the hearing aid automatically or manually switches to directional mode. As a result, hearing aid patients may report decreased performance in noise environments over time. In addition, because directional systems contain more microphone noise relative to omnidirectional arrays, the patient may report hearing additional microphone noise if the system is set to a "directional" response. As a result, routine electroacoustic evaluation of microphone performance is recommended; although, without appropriate equipment, it can be a challenge to document directional performance.

THE SOLUTION: MICROPHONES THAT DO NOT DRIFT

Acuity Directionality, Starkey Hearing Technologies' new, automatic-switching, fully adaptive, dual-microphone, directional system utilizes microphone technology that minimizes microphone drift. These microphones are based on micro-electronic-mechanical systems (MEMS). See Galster and Warren (2014) for a review of MEMS microphone technology. MEMS microphones are produced from a silicon crystal that is more resistant to changes in humidity and temperature cycling than standard electret microphones. Regardless of the environmental conditions, MEMS microphones produce a stable and consistent response that reduces drift and subsequent microphone mismatch over time. The result is a multi-channel, fully adaptive, directional microphone array designed to provide predictable performance over time.

SYSTEM QUALITY TESTING

Studies conducted by Starkey Hearing Technologies and Knowles Electronics investigated long-term microphone performance after accelerated aging testing. These tests subjected hearing aids with MEMS and electret microphones to high humidity, salt fog and temperature cycling. Figure 2 shows the results of accelerated aging tests, which revealed that after extended exposure to high heat and humidity, the magnitude and variation of MEMS microphone drift was greatly reduced relative to the electret microphones. Nominal drift in MEMS microphones was consistent in direction and phase, minimizing mismatch between microphones. In other words, although drift occurred within dual-MEMS microphones, it was consistent across the two microphones such that mismatch was minimized. These test results suggest that repeated calibration of microphone sensitivity is unnecessary and that directional performance is consistent over the life of the hearing instrument with MEMS microphones.

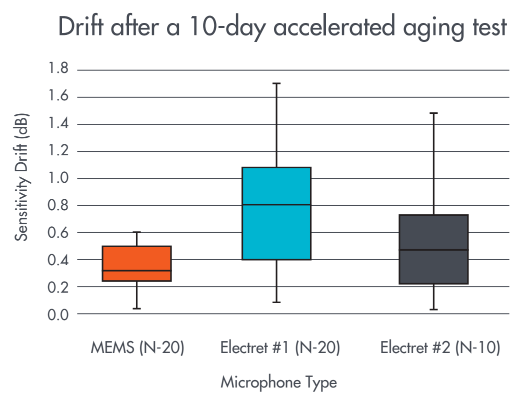


Figure 2: *Sensitivity drift is plotted as box-and-whisker plots after a 10-day accelerated aging test for MEMS microphones and two commonly used electret hearing aid microphones. For each box, the center horizontal line represents the median drift, and the top and bottom horizontal lines represent the interquartile range. Each whisker denotes the minimum and maximum drift per box.*

SYSTEM VERIFICATION AND VALIDATION

Laboratory and field studies compared performance for hearing impaired listeners on speech-in-noise tasks across three directional systems as implemented in Starkey Hearing Technologies hearing aids: 1) Acuity Directionality, 2) a system that automatically switches from an omnidirectional mode into a directional mode with a fixed directional polar response (i.e., dynamic directionality) and 3) a fixed omni-directional response. All study

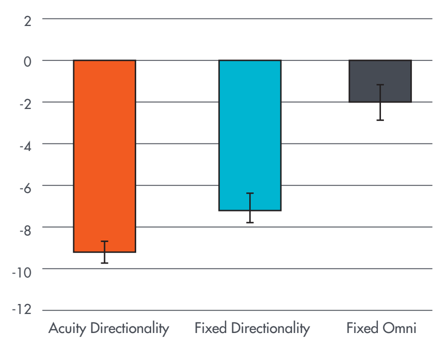


Figure 3: *Mean 50 percent correct SNRs using a mHINT procedure across three directional modes. Error bars represent standard error of the sample mean.*

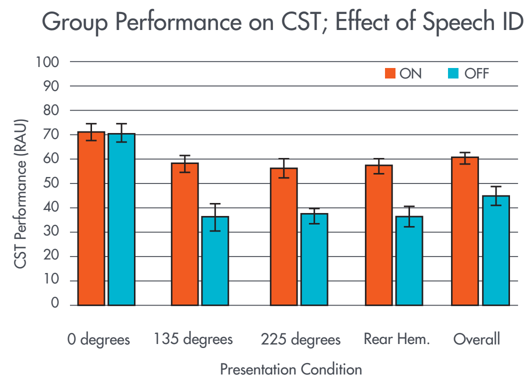


Figure 4: *Modified Connected Speech Test (CST) performance in diffuse noise for Speech ID on (orange) and off (blue) and speech source azimuths of zero degrees, 135 degrees or 225 degrees. Error bars represent standard error of the mean.*

participants were fit to either NAL-NL1 or Starkey Hearing Technologies' proprietary e-STAT® prescriptive targets.

Performance in the lab was measured via a modified Hearing in Noise Test (mHINT) in which speech was presented from either the front or back of the listener while noise was presented from a single speaker or from a combination of speakers surrounding the listener. Results of testing with speech in front and noise at random locations between 90 degrees and 270 degrees are shown in Figure 3 and indicate a significant improvement in listener performance for Acuity Directionality ($F(8,2)=99.66$, $p<.001$), followed by the dynamic directional and omnidirectional modes. Acuity Directionality significantly outperformed the fixed directional condition by over 2dB ($p<.01$), with a maximum advantage of over 4dB and a minimum advantage of 1dB. Modified HINT thresholds in both the fixed directional and Acuity Directionality conditions were better than the omnidirectional mode by approximately 5dB and 7dB, respectively. The magnitude of these performance improvements suggests that Acuity Directionality provides patients with an opportunity for significant improvements.

For approximately three weeks, listeners rated their listening effort using the Magnitude Estimation of Listening Effort (MELE) scale (Humes, Christensen & Bess, 1997). In the MELE task, each participant rated his or her difficulty of listening to speech for multiple specific noisy listening situations on a 0–100 scale where 100 represents the least effort and zero the most effort. Two hearing aid memories were compared: one memory with Acuity Directionality and the other with dynamic directionality (i.e., an automatic directional switching mode with a fixed polar pattern). The memory assignment was blinded, randomized and counterbalanced. Subjectively, listeners not only reported improved speech intelligibility relative to their personal hearing aids, but also rated the ease of listening to be significantly higher in Acuity Directionality than in the dynamic directional program ($F(1,63)=5.282$, $p<.05$).

In addition, Starkey Hearing Technologies' Speech ID, a feature of Acuity Directionality, was validated. Speech ID was designed to preserve speech signals in the rear hemisphere in noisy environments by smoothly steering the null of the polar response away from speech signals originating in the rear hemisphere and extending the lobe of amplification toward the talker. Test performance was compared with Speech ID on and off via a modified Connected Sentence Test (mCST) that presented uncorrelated noise from seven of eight speakers within a circle array and speech from the remaining speaker randomly at zero degrees, 135 degrees or 225 degrees. Figure 4 illustrates that listener performance was significantly improved for speech signals originating from 135 degrees ($t=8.5$, $p<.0001$) and 225 degrees ($t=8.1$, $p<.0001$) by nearly 20 percent when Speech ID was activated and that performance was not affected for speech signals originating in front of the listener. Finally, Figure 5 shows results obtained with Acuity Directionality with Speech ID, a fixed directional and an omnidirectional mode using a mHINT with speech at 180 degrees and uncorrelated noise from seven of eight speakers around the listener. The results in Figure 5 indicate that Acuity Directionality with Speech ID is equivalent to omni-directional performance and nearly 3dB better than a fixed directional response, suggesting that Acuity Directionality with Speech ID protects speech from the back as well as if the hearing aid

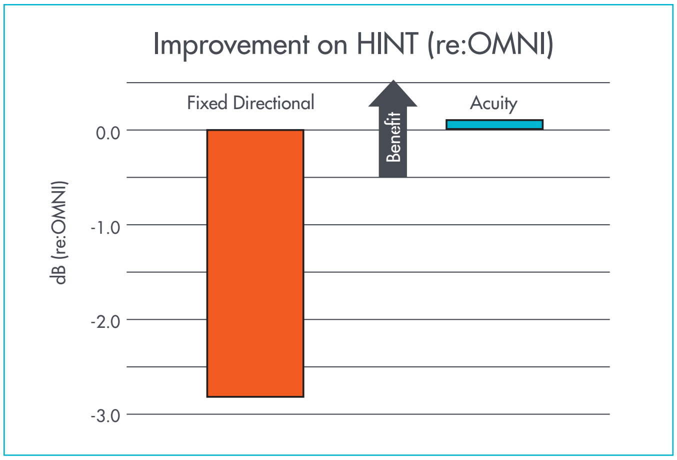


Figure 5: *Modified HINT performance in diffuse noise for a fixed directionality mode (orange) and Acuity Directionality (blue) compared to a fixed omnidirectional response.*

was in an omnidirectional mode. These results suggest Starkey Hearing Technologies' Speech ID will successfully protect valuable speech from rear-facing talkers in noisy environments.

Overall, the results of these studies suggest Starkey Hearing Technologies' Acuity Directionality system will improve performance in background noise for listeners when compared to fixed directional and omnidirectional systems. Because MEMS microphone technology stabilizes microphone sensitivity over time, Acuity Directionality with MEMS microphone technology and Speech ID will likely maintain high directional performance over long-term hearing aid use.

CONCLUSION

While multi-channel adaptive directional microphones are not new to modern hearing aids, Starkey Hearing Technologies has introduced a uniquely robust solution called Acuity Directionality. By leveraging MEMS microphone technology, existing concerns related to microphone drift are addressed. With a solution for long-term performance and evidence to support significant patient benefits, this application of adaptive directionality is one that patients can rely on. Further advancing the performance of Acuity Directionality is Speech ID, Starkey Hearing Technologies' approach to protecting speech from locations other than the front. These systems work as a cohesive group, providing benefits that extend from the laboratory into the real world.

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