AIDED SPATIAL HEARING: ELECTROACOUSTIC AND PERCEPTUAL CONSIDERATIONS

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Abstract

An electroacoustic investigation of aided ILDs and ITDs has been performed using six commercially-available hearing aids that incorporate spatial cue signal processing. The purpose of the study was to measure errors associated with amplification. Two distinct audiograms were tested. When configured according to manufacturers' recommended procedures, all devices produced ILD errors that varied with azimuth and increased with frequency. ITD errors were also common among products. Results suggest that spatial cue signal processing provided by hearing aids has not been optimized and that more research is needed before conclusions about benefit can be made.

Background

Spatial hearing is a complex phenomenon that involves estimates of size and distance as well as approximate direction. The ability to characterize objects in space is facilitated by acoustic, visual, and vibrotactile cues, and is also influenced by cognitive and psychological variables. These variables often change, which can either benefit the listener (e.g. an increase in visibility) or serve as a detriment (e.g. a decrease in the signal to noise ratio). These cues can be quite complex and easily disrupted, particularly when amplification is introduced (Van den Bogaert, et al. (2005); Musa-Shufani, et al. (2006)).

Sounds are affected by the head, ear and torso and these effects provide cues as to an object's spatial characteristics. At high frequencies, the pinna and concha provide directionality cues independently on each side of the head. Head shadow is also observed, which creates the Interaural Level Difference (ILD), a binaural cue that is useful in making left/right determinations. At lower frequencies cues based on the Interaural Time Difference (ITD) become available, which also help in left/right discrimination. When combined with head turning, which serves to facilitate horizontal, vertical and front/back discrimination, the information provided by monaural and binaural cues provides an excellent indication of an auditory object's location in space.

The impact of hearing aids – Modern hearing aids provide not only nonlinear amplification but also feedback control, noise reduction, many types of directionality etc. Some devices also include processing to preserve or enhance spatial cues. These features, while impressive, can also alter the natural acoustic effects that are normally relied upon to spatially perceive sounds. Examples include 1) compression, which can disrupt ILDs, 2) microphone placement, which can alter the head related transfer function, 3) limited bandwidth, which can eliminate high frequency cues, 4) directional systems, which can alter the sound image on one or both sides of the head, 5) clinical considerations (e.g. open *vs.* closed fitting), which can affect sound mixing, and 6) processing delays, which can be both uni- and bilateral.

In an effort to gauge the net effect of amplification on spatial cues, an electroacoustic study was conducted that addressed the following question: "With all features of an amplification system activated, what is the net effect of amplification on the spatial cues available to the listener?" This study examined aided ILDs and ITDs across manufacturers, with all manufacturers' features, particularly those designed to preserve spatial cues, activated. Aided and unaided measurements were made on the Knowles Electronics Manikin for Acoustic Research (KEMAR). The purpose of the investigation was to compare performance across manufacturers under controlled conditions.

Method

Two standard audiograms (Bisgaard et al., 2010) were selected for testing. Audiogram S2 represents a steeply sloping loss with normal hearing through 1000 Hz and a severe loss in the high frequencies. This audiogram would normally be fit using an open configuration but for testing purposes both open and closed domes were evaluated. Each device was configured with the manufacturer's recommended receiver. Audiogram N4 represents a gradually sloping moderate to severe loss. This loss was evaluated under closed dome conditions and was tested using the recommended "high power" receiver.

Top tier Receiver-In-The-Ear devices representing six major manufacturers were selected for analysis. These devices include a range of high-end features, including but not limited to ear-to-ear processing and binaural synchronization. The specifics of the manufacturer's algorithms were largely unknown and these contrasts were allowed to vary among products. Using each manufacturer's fitting software, test devices were programmed to recommended settings, including those for spatial cue enhancement. It should be noted that in doing so numerous features were activated simultaneously, including directionality, noise reduction etc.

The International Speech Test Signal (ISTS; Holube et al., 2010) was used. The signal was presented at 70 dB SPL in quiet for a duration of 30 seconds per measurement. Only the last 10 seconds of each recording was used in the analysis. Testing took place in an anechoic chamber. All measurements were made on KEMAR, which was placed on a turntable that provided precise rotation. Unaided and aided ILDs and ITDs were calculated from simultaneous recordings of the ISTS from two real ear simulators mounted inside the manikin's head. Measurements were made in 2 degree increments. Post processing was completed off line. ILDs were calculated at each angle by comparing coupler output levels at discrete frequencies based on a gammatone filter bank (Glasberg & Moore, 1990). ITDs were obtained by first lowpass filtering the output at 1500 Hz (as ITDs have little to no perceptual effect above this frequency). A cross correlation technique was then used to determine the ITD at each angle.

Results

A series of ILD results based on the S2 (Open) fitting is shown in Figure 1. Each panel shows ILDs as a function of azimuth, with the unaided KEMAR response shown in red and the six aided responses indicated by letter (A–F). ILDs are expected to be near zero at 0 and 180 degrees as the signals delivered to the two ears are nearly identical. Large effects are expected at 90 and 270 degrees where the signals are quite different between ears. The basic question addressed by these data is "How well do the aided responses correspond to the unaided KEMAR response?" At frequencies at or below 1000 Hz the ILDs were quite low and there was good agreement between the unaided and all aided conditions. Above 1000 Hz ILDs increased in magnitude (due to expected head shadow effects), became more complex and showed large mismatches re: unaided.. No product matched the unaided response well and some products produced a signal that was stronger in the ear opposite the signal source (examples indicated by brackets).

The pattern of results shown in Figure 1 was found for all three conditions. This is reflected in Figure 2, which shows mean errors as a function of frequency. In each panel mean errors represent the average of the absolute value of errors measured across azimuth for any given frequency. For the S2 Open condition the mean ILD error was essentially zero up to 1000 Hz.. At higher frequencies the errors increased, in some cases substantially. Similar results were found for the N4 (Closed) condition except for a slight increase in the errors at low frequencies. For the S2 (Closed) condition (not shown) the results were quite similar to N4 (Closed), despite the fact that the prescribed gain for the two audiograms was quite different.

A summary of mean ITD results is shown in Figure 3. The S2 (Open) panel shows good agreement between aided and unaided responses resulting in very low errors for all manufacturers. S2 (Closed) indicates that one manufacturer's device (C) behaved irratically at ~180 degrees, leading to large ITD errors.. The N4 (Closed) panel shows

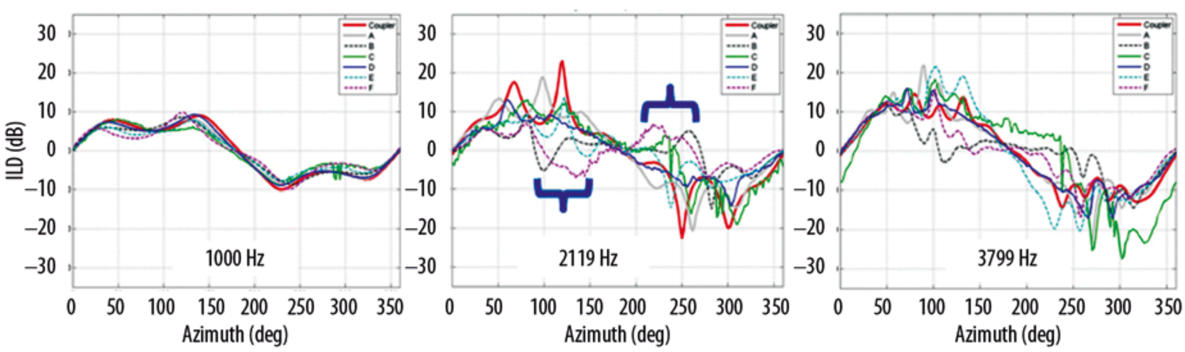

Figure 1. Frequency specific ILDs as a function of azimuth. Unaided KEMAR responses are shown in red. Brackets indicate examples in which higher SPLs were measured in the coupler furthest from rather than nearest to the signal source.

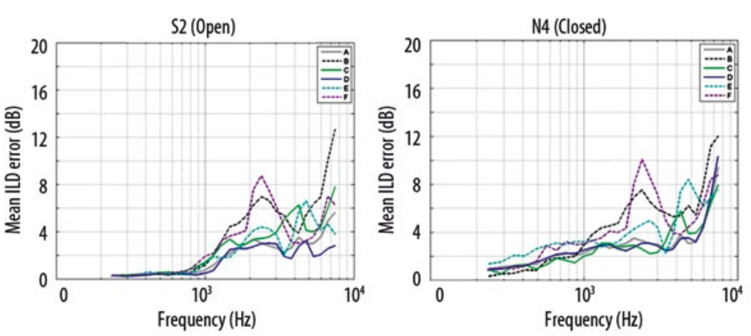

Figure 2. Mean ILDs (averaged across azimuth at each frequency) for the S2 (Open) and N4 (Closed) conditions.

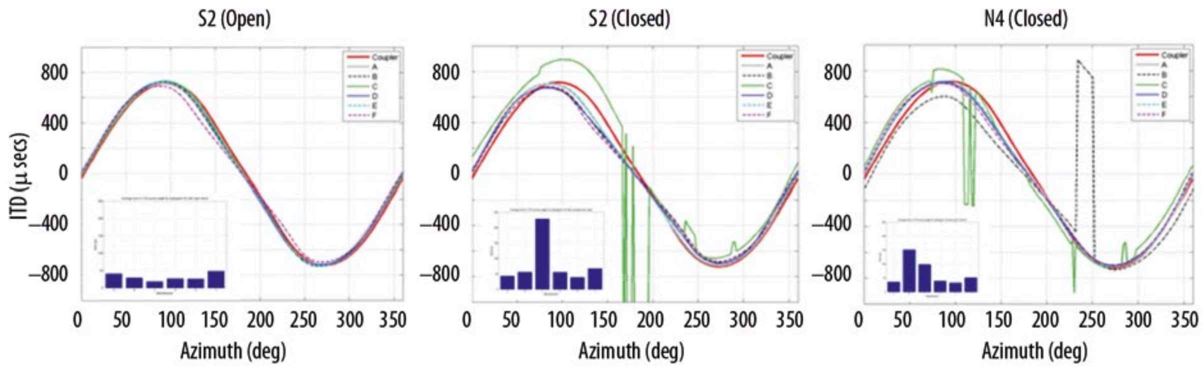

Figure 3. ITDs for the three conditions. Mean errors across manufacturers shown as insets.

that products B and C had irregular patterns at specific azimuths, which resulted in higher mean errors.

Discussion and Conclusions

Given the nature of the test protocol, it is not possible to draw firm conclusions about the effects of specific types of signal processing on spatial cues. However, the objective was to examine whether amplification as a whole, with numerous algorithms functioning simultaneously, disrupts the acoustic cues that are normally available to the listener. Results suggest that complex signal processing can disrupt natural time and level differences that normally provide spatial cues. The data clearly suggest that signal processing that combines multiple algorithms (including those designed to preserve spatial cues) can introduce errors that have the potential to affect spatial perception. The data suggest that no manufacturer currently has an advantage in this regard. Results also suggest that open fittings help to preserve low frequency spatial cues by allowing a mixture of amplified and unamplified sound. For sloping high frequency losses, the combination of (typically) low gain and large vents should serve to minimize spatial cue ambiguities, as well as occlusion effects.

Aided spatial hearing is a complex topic and much more work is needed to optimize benefit for the hearing impaired listener. Efforts are quite likely underway by manufacturers to isolate the effects of specific types of signal processing on spatial cues, but to date, no manufacturer has perfected their spatial cue algorithms, a fact that should be considered when establishing realistic expectations for the patient.

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