Earmold Considerations for Optimal Spatial Hearing in Children with Unilateral Hearing Loss

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Introduction

One of the primary functions of the auditory system is to facilitate spatial hearing. Normal binaural hearing allows listeners to exploit acoustic cues provided by interaural disparities in time and level to identify the location of important sound sources in three-dimensional acoustic space and to enhance speech perception in the presence of competing speech or noise. Psychophysical studies have shown that low-frequency information (below 1500 Hz) codes interaural time disparities (ITD), and high frequency information (above 3000 Hz) codes interaual level disparities (ILD), both of which are critical for sound localization in the horizontal plane. There is however, a great deal of ambiguity in the system in that ITD and ILD cues alone are insufficient to locate sounds originating in the vertical plane. The auditory system resolves the ambiguity by incorporating a monaural spectral cue: the directional-dependent frequency response of the pinna, head and torso, known as the head-related transfer function (HRTF). Listeners appear to incorporate and weight ITD, ILD and HRTF cues to determine the source of sounds, and when conflicting cues are centrally processed, different listeners will weight spatial cues quite differently, learning over time to rely on one cue at the exclusion of the others (Macaulay and Hartmann 2010).

Listeners with normal hearing demonstrate exquisite sensitivity to interaural time and level disparities, and as a result, horizontal sound localization error is very low. For adult listeners, measured mean absolute error for broadband stimuli ranges from ~2° to 9° azimuth with greatest sensitivity between -35° and +35° (for reviews see Durlach and Colburn 1978; Middlebrooks and Green 1991). By age 5 or 6 years, children with normal hearing show comparable adult-like horizontal sound localization acuity (Van Deun et al. 2009; Johnstone, Nábělek and Robertson 2010). As a result, sound localization acuity measurements provide a robust and reliable assessment of binaural function in both child and adult listeners.

Research has shown that unilateral hearing loss (UHL) is particularly detrimental to sound localization acuity (Veihweg and Campbell 1960; Humes, Allen and Bess 1980; Newton 1983; Bess, Tharpe and Gibler 1986; Johnstone et al. 2010). Unilateral hearing loss disrupts spatial hearing because it deprives the listener of critical interaural acoustic cues thereby forcing the listener to rely on conflicting acoustic information. Unfortunately hearing aids can further degrade performance on sound source localization tasks for some listeners with impaired hearing (Hausler, Colburn and Marr 1983; Van den Bogaert, Klasen, Moonen, Van Deun and Wouters 2006; Johnstone et al. 2010).

Research with adult bilateral hearing aid users has shown that spatial hearing measurements such as sound localization and “cocktail party” experiments are sensitive enough to measure the effect of hearing aid technology, earmold venting, microphone settings and compression circuitry on binaural hearing in groups of patients (Nobel and Byrne 1990; Byrne, Sinclair and Noble 1998; Noble, Sinclair and Byrne 1998; Keidser et al. 2006; Van den Bogaert et al. 2006; Marrone, Mason and

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Kidd 2008). The effect of advanced hearing aid technology and earmold type on spatial and binaural hearing in child listeners has not been reported, though Sebkova and Bamford (1981) examined the effect of bilateral hearing aids as compared to a monaural hearing aid on sound localization acuity and/or cocktail party listening in children with bilateral hearing loss. They showed that two hearing aids provided superior spatial hearing than one hearing aid and that there was a correlation between sound localization ability and speech recognition in noise.

Studies using surveys find that many pediatric patients with UHL do not like their hearing aids, eventually stop using them, and show little or no improvement or decrement on conventional, word-discrimination-based behavioral measures of hearing aid performance (Kiese-Himmel 2002; Welch, Welch, Rosen and Dragonette 2004; for review see McKay, Gravel and Tharpe 2008). The measures of hearing aid efficacy typically used in clinical settings appear to lack precision or an ability to capture environmental "real-life" utility of hearing aids in this population. This observation suggests that more robust means of assessing hearing aid performance in children with UHL are needed to sufficiently differentiate the efficacy of hearing aid technologies and incorporate them into evidence-based practice. It has been suggested that measurements of spatial hearing may be critical in identifying beneficial differences in hearing aid and/or earmold technology in that they are robust and precise, and children rely on spatial hearing to navigate complex acoustic environments (Johnstone et al. 2010).

Method

The test equipment and environment were identical to that described by Johnstone, Nábělek and Robertson (2010). Prior to testing, real ear verification of the hearing aid fitting relative to the prescriptive target reported in the clinic chart was done using a Verifit system. All testing was done in a sound-treated booth (IAC, 2.2 x 1.8m). The children sat at a chair-style desk facing a semicircular arc. For the localization tests an array of 15 loudspeakers (Cambridge SoundWorks Center/Surround IV; matched within 1 dB at 100 to 8000 Hz) were placed on the arc at 10° intervals from -70° to +70° azimuth (see Figure 1A). A small picture was attached below each loudspeaker. These pictures corresponded to an arc of pictures displayed on a computer screen placed in front of the listener below the loudspeaker at 0° azimuth.

For the spatial speech recognition task two loudspeakers were placed at the center at 0° and one loudspeaker was placed on the arc at -90° and another at +90° as was first described by Litovsky (2005) (see Figure 1B). The target stimuli consisted of 25 two-syllable children's spondee words obtained from Auditec recorded with a male voice and RMS equalized. The interfering speech stimuli consisted of digitized sentences from the Harvard IEEE list (Rothauser et al. 1969) recorded with a female voice.

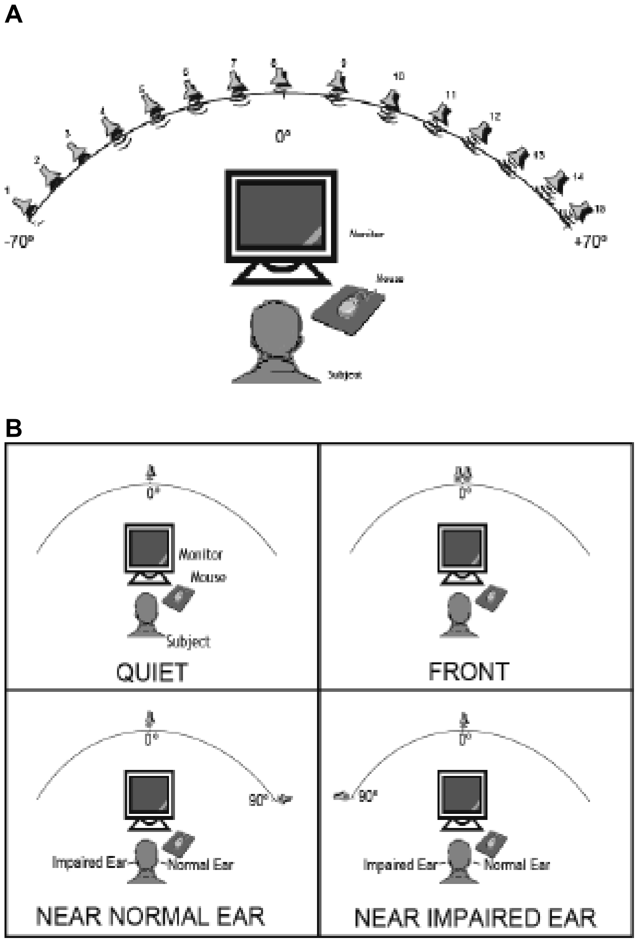

Figure 1. A schematic diagram of the testing environment used to measure spatial hearing. Panel A of this figure shows the set up for the horizontal sound localization experiment: an array of 15 loudspeakers placed on an arc, with 1 meter radius, between -70° and +70°, separated by 10°. Panel B of this figure shows the set up for the spatial speech recognition experiment: one loudspeaker, used to present the target spondee, was placed on the arc at 0° in front of the listener. Three additional loudspeakers, used to present the speech interferers, were placed on the arc at 0°, and at +90° and -90°. This figure was adapted and used with permission here by Taylor and Francis from: Litovsky, Johnstone and Godar (2006). Benefits of bilateral cochlear implants and/or hearing aids in children. *International Journal of Audiology* 45(Suppl.1): S78–S91, page S84. Permission conveyed through Copyright Clearance Center.

Hardware, including a Tucker Davis Technologies (TDT) System III (RP2, PM2, AP2) in conjunction with an IBM PC host, controlled stimulus presentation. It also controlled the multiplexer used for loudspeaker switching and amplification. Software for the stimulus presentation and data collection operated on a custom written MatLab platform.

Sound Localization Procedure

The children sat in a chair-style desk facing the loudspeaker at 0° azimuth. A computer screen was placed below the loudspeaker, and during individual trials the children were reminded to keep their head directed toward 0° azimuth. If any noticeable head movement was detected, the data for that trial were discarded and an additional trial was given. On the desktop a computer mouse and mouse pad were placed. The children were told to sit still, face forward, and look at the computer screen during the trial. A single trial consisted of a single presentation of the word "baseball" recorded with a male voice at a sampling rate of 44.1 kHz, RMS equalized, and stored as a WAV file. The stimulus "baseball" was presented randomly to each speaker a total of 10 times for a total of 150 trials for each listening condition tested.

Each loudspeaker had a different picture below it. The children were instructed to report where the word "baseball" originated by clicking on the picture on the computer screen that matched the picture under the loudspeaker from which the sound was perceived to have originated. After each response, feedback was provided such that the correct-location icon flashed on the computer screen. Feedback was provided for two of the children in this study (UAAA and UAAE). The feedback feature was disabled for UAAF (a child with autism spectrum disorder) who expressed extreme frustration and anxiety when he made localization errors. When the feedback feature was disabled he appeared to relax and participated without any further expressed anxiety or delay.

Localization acuity was measured by computing RMS error for each angle and averaging it over the entire array for each listening condition for each child.

Spatial Speech Recognition Procedure

Figure 1B illustrates the four listening conditions: Quiet (target at 0°, no interferers); Front (target at 0°, interferers at 0°); Near Normal Ear (target at 0°, interferers at 90° to the side towards the ear with normal hearing); and Near Impaired Ear (target at 0°, and interferers at 90° to the side towards the ear with impaired hearing). This experimental design was adapted from that used with children with sequential bilateral cochlear implants or with a cochlear implant and a hearing aid (Litovsky, Johnstone and Godar 2006). Prior to testing, each child was briefly familiarized with all spondee target words. During the familiarization task the child was asked to identify the pictured spondee words. Each child was able to readily identify each spondee word.

During the testing the children sat in a chair-style desk facing the loudspeakers in front at 0° azimuth. A computer screen was placed below the loudspeaker and during individual trials the children were reminded to keep their head directed toward 0° azimuth. If any noticeable head movement was detected the data for that trial were discarded and an additional trial was given. On the desktop a computer mouse and mouse pad were placed. The children were told to sit still, face forward, and look at the computer screen during the trial.

The speech recognition task consisted of a 4-alternative-forced-choice (4-AFC) procedure (Litovsky 2005). On each trial, a word from the Children's Spondee List was randomly selected from a closed set of 25 target words recorded with a male voice. The target word was preceded by the phrase "Ready? Point to the…" also recorded with a male voice. The child was asked to select a picture that matched the presented target word from a group of 4 pictures displayed on a computer screen. Only one picture matched the actual target word presented.

In listening conditions containing interfering sounds, the interfering speech started first, followed by the presentation of the target spondee. The interfering speech continued after the target was turned off for approximately 1 – 2 seconds. The children were instructed to listen carefully to the male voice and ignore the female voices. On every trial a word from the list of spondees was chosen randomly from the closed set of 25 targets. The randomization algorithm ensured that for every child, on average, all 25 words were used an equal number of times.

Speech recognition threshold (SRT) adaptive tracks were collected employing algorithm rules described in great detail elsewhere (Litovsky 2005; Johnstone and Litovsky 2006; Garadat and Litovsky 2007). Basically, at the beginning of a listening condition the level of the target started at 60 dB SPL and a modified 3-down-1-up adaptive tracking method was used to increase the level when an incorrect response was given and decrease the level when three consecutive correct responses were given. Testing would stop after four reversals. When interferers were present the level of the interferer was held constant at 60 dB SPL.

A constrained maximum likelihood (MLE) method of parameter estimation developed by Wichmann and Hill (2001a, 2001b) was used to estimate speech recognition threshold (SRT) as reported by Johnstone and Litovsky (2006). All data from each adaptive track were fit to a logistic function and the inverse of the function at a specific probability level was taken. Psychometric functions were set to a lower bound, "chance" level of 0.25. Given that an adaptive 3-down-1-up procedure was used, SRT corresponded to the level of the target on the psychometric function where performance was approximately 79.4% as estimated by Levitt (1971).

Three Case Studies Involving Open Fit Earmolds in Children with UHL

In this section we present individual measures of spatial hearing, that is, aided and unaided sound localization acuity, and spatial speech recognition data from three pediatric patients whose audiograms suggested that they would be appropriate candidates for use of an open fit earmold because of normal low frequency hearing in both ears (see Figure 2). Table 1 provides demographic information regarding these three children with UHL including: age at study participation; age at diagnosis; age at first hearing aid fitting (intervention); impaired ear (L or R); degree of hearing loss; hearing aid make; microphone settings; earmold style; vent size; and reported hearing aid use (rarely, only at school, or full time). The demographic data were obtained from four sources: the child's parent; the child's audiology clinic record; the child; and by examining the child's hearing aid, earmold, and audiogram. Two of the children (UAAA and UAAE) were in public schools and had an Individualized Education Program (IEP) in place for learning disability and emotional disorder, respectively. UAAF was currently home schooled but did have an IEP in place for autism spectrum disorder when he previously attended public school. These case studies serve to illustrate the potential utility of spatial hearing measurements in clinical practice, as well as the importance of using open fit earmolds when justified by normal low frequency pure tone thresholds.

All three patients participated in a recent study evaluating the effect of hearing aid use on sound localization acuity in children with UHL who wear a hearing aid in the impaired ear (Johnstone et al. 2010). Their parents or legal guardians gave consent and the children gave assent to return to the lab for further testing to determine if the use of an open fit earmold would improve spatial hearing measures. Using the methods described in the previous section each child was tested in three conditions: unaided; aided with their standard skeleton earmold, and aided with an open fit earmold. The order of the testing was completely randomized for UAAA whose hearing aid allowed for the standard skeleton and the open fit earmold to be switched out easily. For the other two children (UAAE and UAAF) the hearing aid had to be retrofitted with the open fit earmold and the skeleton earmold could not be used again. This meant that they were tested unaided and with the skeleton earmold first and then tested again with the open fit mold. Unaided testing was also repeated to control for any learning effects that might have contributed to the measured performance.

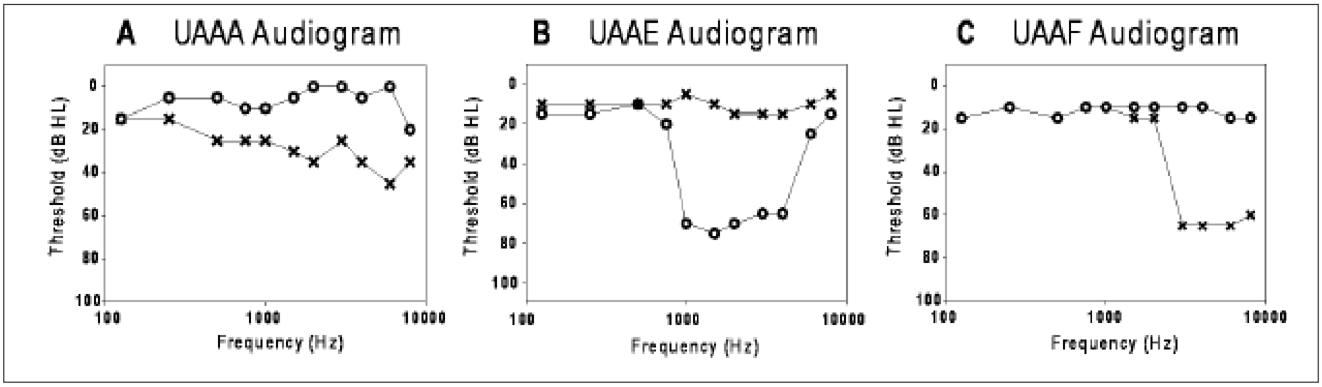

Figure 2. Pure tone, air-conduction thresholds for three children (A-C) with UHL who were selected to use an open fit earmold based on evidence of some normal low-frequency hearing in both ears.

Subject	Sex	Age (y)	Age (y) Dx Loss	Age (y) First HA Fit	HA Use Duration (y)	Imp Ear / Deg Loss	HA Make	Model	Fitting Target	Signal Process	Mic Mode	Earmold Type & Vent	Use
UAAA	M	13	5	12	1	L / MM	Widex	Bravo 2	NAL	WDRC NC	Dir	Skeleton 1 mm	School Only
UAAE	F	11	7	7	4	R / MM CB	Phonak	Maxx 311	DSL [i/o]	dWDRC dNC	Dir	Skeleton .03 mm	School Only
UAAF	M	9	3	3.5	2.5	L / MM	Phonak	Eleva 411	DSL v5	dWDRC	dAZ Omni	Skeleton 1 mm	All Day

Table 1. Subject Demographic Information.

Case 1: UAAA

This case study involved a 13-year-old male with mild-to-moderate UHL in his left ear that was diagnosed at age 5 years. Intervention occurred at age 12 years when he was fit with his first hearing aid: a Widex Bravo 2, with wide dynamic range compression (WDRC), directional microphone. He used a skeleton earmold with large vent. A recent audiogram (see Figure 2A) showed normal hearing sensitivity in the impaired ear at 125 and 250 Hz with a difference of 10 dB or less between the two ears at these two frequencies. UAAA reported that he wore his hearing aid only during school. The normal hearing sensitivity measured in the lowest frequencies met our criteria to try an open fit earmold. An open fit earmold was made for UAAA.

When the open fit earmold was ready, localization acuity was measured in the laboratory under three listening conditions: unaided; aided with skeleton earmold; aided with open fit earmold. The order of the listening conditions was randomized. UAAA was allowed to wear his hearing aid with the open fit earmold for approximately 1.5 hours prior to testing to acclimatize to it. The effect of earmold changes on localization acuity can be seen in Figures 3A, 3B, and 3C and is measured using RMS error (degrees azimuth). Smaller localization error is associated with better localization acuity. Figure 4B shows that when the skeleton earmold was used, localization acuity was degraded relative to unaided performance (Figure 3A). When the open earmold was used localization acuity was improved relative to the vented skeleton earmold but did not still reach unaided values (Figure 3C).

Figure 4A shows the effect of the skeleton earmold and the open fit earmold on SRT obtained when speech interferers were located either in Front, Near the Normal Ear (NNE), or Near the Impaired Ear (NIE). The bold line represents unaided SRT. To compute binaural benefit, aided scores were subtracted from unaided scores. A positive number (in dB) represents a binaural/bilateral improvement in SRT and a negative number (in dB) reflects binaural/bilateral interference. Figure 4A shows that when UAAA used the skeleton earmold his SRTs were poorer than unaided (as shown by bars below the bold horizontal line) when the interfering speech was located in front of him. He showed some small benefit when the speech interferers were located NIE or NNE (bars above the bold horizontal line). When UAAA used the open fit earmold binaural/bilateral SRTs were better than unaided listening in all listening conditions with interfering speech.

In addition to the objective evidence for improved spatial hearing when using the open fit earmold, UAAA also reported a subjective substantial improvement in sound quality after wearing the new earmold for only a few minutes. He reported that "everything sounded much better" and that it was much easier to hear. He continues to use the open fit earmold with his hearing aid.

Case Study 2: UAAE

This case study involved an 11-year-old female with a "cookie bite" UHL in her right ear that was diagnosed at age 7 years. She was fitted shortly after the diagnosis with her first hearing aid: a Phonak Maxx 311, with WDRC, digital noise cancellation (dNC), directional microphone, and used a skeleton earmold with a pressure vent. A recent audiogram (see Figure 2B) showed normal hearing sensitivity in the impaired ear at 250 – 750 Hz and at 8000 Hz with a difference of 10 dB or less between both ears at these frequencies. UAAE reported that she wore her hearing aid part-time during school hours only.

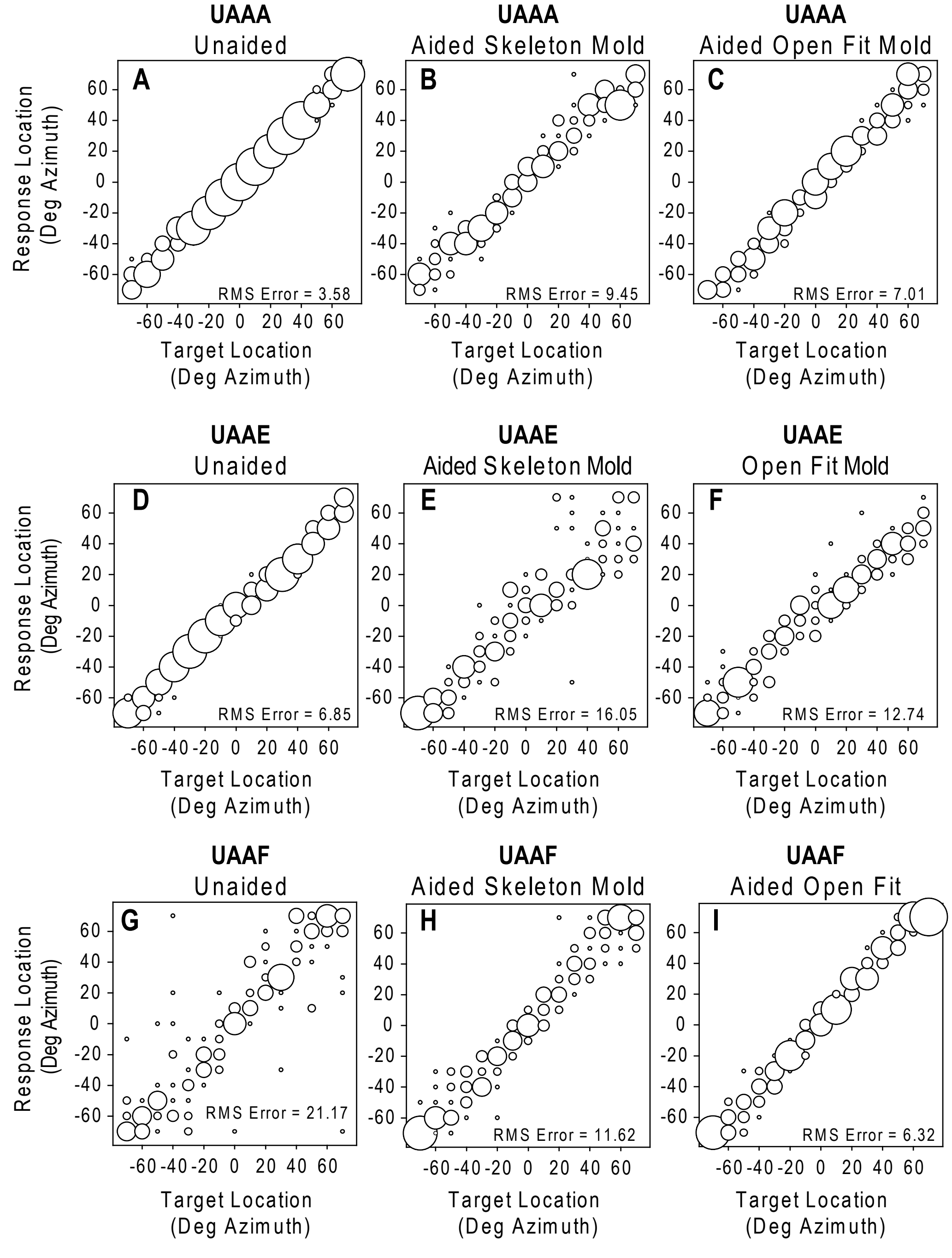

Figure 3. Localization results for the three children with UHL. Each panel shows the proportion of localization responses for every azimuthal location tested, proportional to the size of the circles. Perfect performance would result in large, equal-sized circles perfectly aligned on the diagonal. Examples are shown from the three subjects arranged in rows. Results from UAAS (13 years) are arranged on the top row, results from UAAE (11 years) in middle row, and results from UAAF (9 years) are arranged on the bottom row. Results for aided conditions progress from left (unaided hearing) to middle (aided with vented skeleton earmold) to right (aided with open fit earmold). Average RMS error for each child is reported at the bottom right of each panel. Smaller error equals better localization acuity.

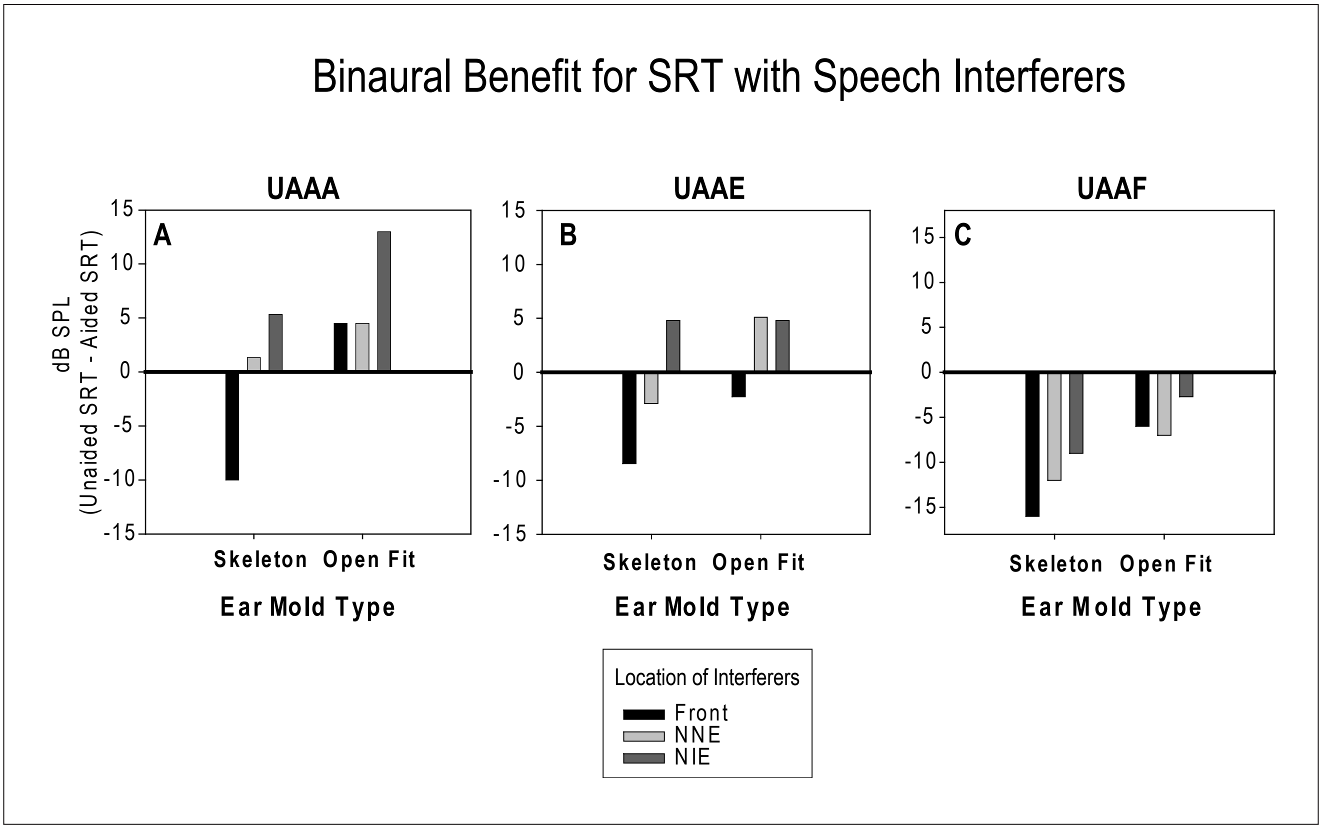

Figure 4. Spatial speech recognition test results for the three children with UHL. Each panel shows the change in SRT relative to unaided (the bold horizontal line). Aided SRT was subtracted from unaided SRT and the results for each listening condition when interferers were present (Front, NNE, NIE) are graphed. Positive values indicate bilateral/binaural benefit. Negative values indicate bilateral/binaural interference or decrement.

It was decided that UAAE met our criteria to try an open fit earmold. Her legal guardian gave consent for UAAE to try an open fit earmold. Her hearing aid was retrofitted with an open fit earmold by the manufacturer.

Localization acuity was measured for UAAE as it was done for UAAA. However, UAAE was allowed to wear her hearing aid with the open fit earmold for approximately 30 minutes prior to testing. The effect of earmold acoustics on localization acuity can be seen in Figure 3D, 3E and 3F and is measured using RMS error (degrees azimuth). Smaller localization error is associated with better localization acuity. Figure 3E shows that when the skeleton earmold was used localization acuity was degraded (RMS error more than doubled) relative to unaided performance (Figure 5D). When the open earmold was used localization acuity was improved relative to the vented skeleton earmold but did not reach unaided values (Figure 3F).

Figure 4B shows the effect of the skeleton earmold and the open fit earmold on SRT obtained when speech interferers were located either in Front, Near the Normal Ear (NNE), or Near the Impaired Ear (NIE). The bold line represents unaided SRT. To compute binaural benefit, aided scores were subtracted from unaided, thus binaural benefit would result in a positive dB improvement in SRT and a negative number would reflect binaural interference. When UAAE used the skeleton earmold, binaural interference was evident when the interfering speech was located in front or NNE. She showed benefit only when the speech interferers were located NIE (probably due to head shadow effects). When UAAE used the open fit earmold, SRTs were better/lower with the hearing aid on than without the hearing aid in all listening conditions with interfering speech. However, binaural benefit was present when the interfering speech was located NNE and NIE but not when the speech interferers were located in front.

The objective evidence for UAAE which showed improved spatial hearing using the open fit earmold was also supported by immediate, spontaneous subjective reports from UAAE after wearing the new earmold for only a few minutes. She reported that her own voice and the voice of others "sounded so much better – more natural." She became emotional when she talked about how much better everything sounded to her with the open fit earmold. She continues to use the open fit earmold with her hearing aid.

Case Study 3: UAAF

This case study involves a 9-year-old boy with autism spectrum disorder and a unilateral high-frequency hearing loss in the left ear. He was diagnosed with this hearing loss at age 3 years and was fitted by age 3.5 years with a Phonak Eleva 411, with WDRC, and microphone fixed in the omni-directional setting. He used a skeleton earmold with a large vent. A recent audiogram showed normal hearing sensitivity in the impaired ear between 125 and 2000 Hz (with a difference of 10 dB or less between the two ears at these frequencies) and a moderate sensorineural hearing loss between 3000 and 8000 Hz in the left ear (see Figure 2C). The normal hearing sensitivity in the lowest frequencies met our criteria to try an open fit earmold. UAAFs mother gave consent for her son's hearing aid to be retrofitted with an open fit earmold by the manufacturer.

Localization acuity was first measured in the laboratory under two listening conditions: unaided and aided with a skeleton earmold. After the hearing aid was retrofitted with the open fit earmold UAAF returned to the laboratory and was tested under two listening conditions: unaided and aided with open-fit earmold in place. UAAF was allowed to wear his hearing aid with the open fit earmold for approximately 30 minutes prior to testing to acclimatize to it. Unaided values did not change between the two test sessions. Figures 3G, 3H, and 3I show the effect of earmold acoustics on localization acuity. When the skeleton earmold was used localization acuity was improved relative to unaided performance (localization error was halved). When the open earmold was used localization acuity was improved relative to the skeleton earmold (RMS error was halved again). Unaided localization acuity was measured a second time and it was unchanged from the first visit. It should also be noted that UAAF showed better localization acuity at the larger angles of separation (as denoted by the large circles on the graphs) than near the center of the loudspeaker array. This response pattern is different from adults and children with normal hearing who typically show better spatial hearing for the smaller angles at midline than for the wider angles.

Figure 4C shows the effect of the skeleton earmold and the open fit earmold on SRT obtained when speech interferers were located either in Front, NNE, or NIE. The bold line represents unaided SRT. To compute binaural benefit, aided scores were subtracted from unaided scores, thus binaural benefit would result in a positive dB improvement in SRT, and a negative number would reflect binaural interference. When UAAF used the skeleton earmold, SRTs were poorer/higher than unaided in all conditions involving interfering speech. When he used the open fit earmold, SRTs improved relative to the skeleton earmold but were still poorer than unaided SRTs in all listening conditions.

During the experiment, UAAF did not say much about the new earmold. However his mother contacted us later to tell us that her son "loved the new earmold" and had told her he would not wear the old earmold ever again. She also indicated that he'd stopped resisting putting the hearing aid on in the morning or fussing about it during the day since he started using the new earmold. He continues to use the open fit earmold with his hearing aid.

Discussion

The use of open fit earmolds in these children with UHL with normal low frequency hearing appears to have a beneficial effect on individual measures of spatial hearing when compared to the use of a traditional skeleton earmold with venting. All three children showed improved localization acuity and better (lower) SRTs for speech when interfering speech was present when using an open fit earmold. However, the results of the three case studies do not provide clear indication whether using the open fit earmold with hearing aid amplification in pediatric patients with UHL will provide binaural or bilateral advantage in all spatial hearing demands. One child (UAAF) showed aided bilateral/binaural horizontal sound localization benefit, but the other two children (UAAA, UAAE) did not. The lack of bilateral benefit for horizontal sound localization might be related to the age at which the older children received hearing aid intervention. UAAA received his first hearing aid at age 12 years and UAAE at age 7 years and as a result, these children likely learned to localize monaurally. By comparison, UAAF received his first hearing aid at age 3.5 years and this may explain why he profits from his hearing aid when performing sound localization tasks. Johnstone et al. (2010) showed that children with UHL who received a hearing aid before age 5 years showed bilateral benefit on horizontal sound localization measures, whereas children who were older than 5 years when they received their first hearing aid did not.

The current case studies also show how hearing aid amplification for children with UHL affects speech perception in a background of interfering speech. Good word discrimination in a "cocktail party" environment is probably more important than good sound localization (Johnstone et al. 2010). All of the children presented in these case studies were able to use spatial cues to improve SRTs when the interfering speech was located 90° to the left or right (Near the Normal Ear or Near the Impaired Ear) while aided using an open fit earmold, as compared to aided using a traditional skeleton earmold. All children reported immediate and dramatic subjective improvement in sound quality when using an open fit earmold. However, only two children (UAAA and UAAE) showed bilateral/binaural aided improvement relative to unaided SRTs. One child (UAAF) continued to show degraded aided SRTs relative to unaided – even with the open fit earmold present. Marrone et al. (2008) suggested that the relationship between hearing aid use and speech perception in cocktail party listening environments is complex and was most likely related to hearing loss, hearing aid use and selective auditory attention. It may well be that UAAF may have language and/or auditory attention deficits related to autism spectrum disorder that might have affected his SRT in competing speech above and beyond his hearing impairment.

Finally it is not clear how learning and/or inconsistent daily hearing aid use may have affected the results obtained in these three case studies. The test items and tasks were kept deliberately easy to avoid or reduce learning effects. Nonetheless it is impossible to eliminate them entirely from any experiment involving human subjects and repeated measures. It is hypothesized here that early diagnosis and hearing aid fitting coupled with appropriate open fit earmold technology (when indicated by some normal low-frequency hearing) may encourage children with UHL to wear their hearing aid more regularly and with fewer complaints. If this could be accomplished it could, in theory, enhance the likelihood of binaural benefit developing over time in this population of patients due both to maturation/learning and to consistent ILD and ITD input due to optimal earmold acoustics and amplification.

References

Bess, F.H., Tharpe, A.M., and Gibler, A.M. 1986. Auditory performance of children with unilateral sensorineural hearing loss. *Ear and Hearing* 7: 20–6.

Byrne, D., Sinclair, S., and Noble, W. 1998. Open earmold fittings for improving aided auditory localization for sensorineural hearing losses with good high-frequency hearing. *Ear and Hearing* 19: 62–71.

Durlach, N., and Colburn, H.S. 1978. Binaural phenomena. In E.X. Carterette and M. Friedman (eds.), *Handbook of perception Vol. IV* (pp.405–466). New York: Academic Press.

Garadat, S.N. and Litovsky, R.Y. 2007. Speech intelligibility in free field: Spatial unmasking in preschool children. *Journal of the Acoustical Society of America* 121: 1047–55

Hausler, R., Colburn, H.S., and Marr, E. 1983. Sound localization in subjects with impaired hearing: Spatial-discrimination and interaural-discrimination tests. *Acta Oto-laryngo-logica Suppl.* 400: 1–62.

Humes, L.E., Allen, S.K., and Bess, F.H. 1980. Horizontal sound localization skills of unilaterally hearing-impaired children. *Audiology* 19: 508–518.

Johnstone, P.M., Nábělek, A.K., and Robertson, V.S. 2010. Sound localization acuity in children with unilateral hearing loss who wear a hearing aid in the impaired ear. *Journal of the American Academy of Audiology* 21: 522–34.

Johnstone, P.M., and Litovsky, R.Y. 2006. Effect of masker type and age on speech intelligibility and spatial release from masking in children and adults. *Journal of the Acoustical Society of America* 120: 2177–1289.

Keidser, G., Rohrseitz, K., Dillon, H., Hamacher, V., Carter, L., Rass, U., and Convery, E. 2006. The effect of multi-channel wide dynamic range compression, noise reduction, and the directional microphone on horizontal localization performance in hearing aid wearers. *International Journal of Audiology* 45: 563–579.

Kiese-Himmel, C. 2002. Unilateral sensorineural hearing impairment in childhood: Analysis of 31 consecutive cases. *International Journal of Audiology* 41: 57–63.

Levitt, H. 1971. Transformed up-down methods in psychophysics. Journal of the Acoustical Society of America 49: 467–477.

Litovsky, R.Y. 2005. Speech intelligibility and spatial release from masking in young children. *Journal of the Acoustical Society of America* 117: 3091–3099.

Litovsky, R.Y., Johnstone, P.M., and Godar, S. 2006. Benefits of bilateral cochlear implants and/or hearing aids in children. *International Journal of Audiology* 45(Suppl.1): S78–S91.

Macaulay, E.J., and Hartmann, B. 2010. The acoustical bright spot and mislocalization of tones by human listeners. *Journal of the Acoustical Society of America* 127: 1440–1449.

McKay, S., Gravel, J., and Tharpe, A.M. 2008. Amplification considerations for children with minimal or mild bilateral hearing loss and unilateral hearing loss. *Trends in Amplification* 12: 43–54.

Marrone, N., Mason, C.R., and Kidd, G. Jr. 2008. Evaluating the benefit of hearing aids in solving the cocktail party problem. *Trends in Amplification* 12: 300–315.

Middlebrooks, J.C., and Green, D.M. 1991. Sound localization by human listeners. *Annual Review of Psychology,* 42:135159.

Newton, V.E. 1983. Sound localization in children with a severe unilateral hearing loss. *Audiology* 22: 189–198.

Noble, W., and Byrne, D. 1990. A comparison of different binaural hearing aid systems for sound localization in the horizontal and vertical planes. *British Journal of Audiology* 24: 335–346.

Noble, W., Sinclair, S., and Byrne, D. 1998, Improvements in aided sound localization with open earmolds: Observations in people with high-frequency hearing loss. *Journal of the Acoustical Society America* 9: 25–34.

Rothauser, E.H., Chapman, W.D., Guttman, N., Nordby, K. S., Silbigert, H.R., Urbanek, G.E., and Weinstock, M. 1969. IEEE Recommended practice for speech quality measurements." *IEEE Transactions in Audio Electroacoustics.* 17: 225–246.

Sebkova, J., and Bamford, J.M. 1981. Evaluation of binaural hearing aids in children using localization and speech intelligibility tasks. *British Journal of Audiology* 15:125–32.

Van den Bogaert, T., Klasen, T.J., Moonen, M., Van Deun, L., and Wouters, J. 2006. Horizontal localization with bilateral hearing aids: Without is better than with. *Journal of the Acoustical Society of America* 119: 515–26.

Van Deun, L.,van Wieringen, A., Van den Bgaert, T., Scherf, F., Offeciers, F.E., Van de Heyning, P.H., Desloovere, C., Dhooge, I.J., Deqqoui, N., De Raeve, L., and Wouters, J. 2009. Sound localization, sound lateralization, and binaural masking level differences in young children with normal hearing. *Ear and Hearing* 30: 178–90.

Viehweg, R., and Campbell, R. 1960. Localization difficulty in monaurally impaired listeners. *Annals of Otology Rhinology Laryngology* 69: 662–34.

Welsh, L.W., Welsh, J.J., Rosen, L.F., Dragonette, J.E. 2004. Functional impairments due to unilateral deafness. *Annals of Otology Rhinology Laryngology* 113: 987–993.

Wichmann, F.A., and Hill, J. 2001a. The psychometric function. I. Fitting, sampling, and goodness of fit. *Perception and Psychophysics* 63: 1290–1313.

Wichmann, F.A., and Hill, J. 2001b. The psychometric function. II. Bootstrap-based confidence intervals and sampling. *Perception and Psychophysics* 63: 1314–29.