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# Open-Fit Domes and Children with Bilateral High-Frequency Sensorineural Hearing Loss: Benefits and Outcomes

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**Abstract**

**Background:** Open-fit domes (OFDs) coupled with behind-the-ear (BTE) hearing aids were designed for adult listeners with moderate-to-severe bilateral high-frequency hearing loss (BHFL) with little to no concurrent loss in the lower frequencies. Adult research shows that BHFL degrades sound localization accuracy (SLA) and that BTE hearing aids with conventional earmolds (CEs) make matters worse. In contrast, research has shown that OFDs enhance spatial hearing percepts in adults with BHFL. Although the benefits of OFDs have been studied in adults with BHFL, no published studies to date have investigated the use of OFDs in children with the same hearing loss configuration. This study seeks to use SLA measurements to assess efficacy of bilateral OFDs in children with BHFL.

**Purpose:** To measure SLA in children with BHFL to determine the extent to which hearing loss, age, duration of CE use, and OFDs affect localization accuracy.

**Research Design:** A within-participant experimental design using repeated measures was used to determine the effect of OFDs on localization accuracy in children with BHFL. A between-participant experimental design was used to compare localization accuracy between children with BHFL and age-matched controls with normal hearing (NH).

**Study Sample:** Eighteen children with BHFL who used CE and 18 age-matched NH controls. Children in both groups were divided into two age groups: older children (10–16 yr) and younger children (6–9 yr).

**Data Collection and Analysis:** All testing was done in a sound-treated booth with a horizontal array of 15 loudspeakers (radius of 1 m). The stimulus was a spondee word, "baseball": the level averaged 60 dB SPL and randomly roved (±8 dB). Each child was asked to identify the location of a sound source. Localization error was calculated across the loudspeaker array for each listening condition.

**Results:** A significant interaction was found between immediate benefit from OFD and duration of CE usage. Longer CE usage was associated with degraded localization accuracy using OFDs. Regardless of chronological age, children who had used CEs for <6 yr showed immediate localization benefit using OFDs, whereas children who had used CEs for >6 yr showed immediate localization interference using OFDs. Development, however, may play a role in SLA in children with BHFL. When unaided, older children had significantly better localization acuity than younger children with BHFL. When compared to age-matched controls, children with BHFL of all ages showed greater localization error. Nearly all (94% [17/18]) children with BHFL spontaneously reported immediate own-voice improvement when using OFDs.

**Conclusions:** OFDs can provide sound localization benefit to younger children with BHFL. However, immediate benefit from OFDs is reduced by prolonged use of CEs. Although developmental factors may play a role in improving localization abilities over time, children with BHFL will rarely equal that

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of peers without early use of minimally disruptive hearing aid technology. Also, the occlusion effect likely impacts children far more than currently thought.

**Key Words:** children, hearing loss, outcomes

**Abbreviations:** ANOVA = analysis of variance; BHFL = bilateral high-frequency sensorineural, hearing loss; BTE = behind-the-ear; CE = conventional earmold; HA = hearing aid; LTASS = long-term average speech spectrum; NH = normal hearing; OFD = open-fit dome; RMS = root mean square; SD = standard deviation; SII = speech intelligibility index; SLA = sound localization accuracy; SPL = sound pressure level

## INTRODUCTION

In this study, we describe the results of an experiment that involved replacing conventional earmolds (CE) with open-fit domes (OFDs) on the hearing aids of children with normal low-frequency hearing and bilateral, high-frequency, sensorineural hearing loss (BHFL) and measuring the immediate effects on their horizontal sound localization accuracy (SLA). While much is known about the effect of BHFL, binaural hearing aids, and OFDs on SLA in adult listeners (e.g., Häusler et al, 1983; Noble et al, 1994; Byrne et al, 1996; Byrne et al, 1998; Noble et al, 1998; Van den Bogaert et al, 2006; Alworth et al, 2010), relatively little is understood about how these factors affect SLA in young children. In adult listeners, the presence of BHFL degrades sound localization performance (Häusler et al, 1983; Noble et al, 1994; Alworth et al, 2010) and hearing aids with CE degrade performance further (Van den Bogaert et al, 2006). However, when OFDs are used, adults with BHFL perform as well aided as unaided (Alworth et al, 2010) and report additional benefits such as improved hearing aid sound quality (Goode and Krusemark, 1999; Alworth et al, 2010), improved own-voice quality (Alworth et al, 2010), and improved externalization of sound (Boyd et al, 2012). As a result, OFDs have been widely incorporated into audiology practice to fit adults with BHFL (Kuk and Baekgaard, 2008). Conversely, the lack of research evidence regarding the use of OFDs in young children with BHFL has made pediatric audiologists reluctant to use OFDs routinely in clinical practice.

The improvement in SLA afforded by OFDs in adult listeners is attributed to restoration of essential low-frequency acoustic cues below 1500 Hz that encode interaural time disparities that are disrupted when the external ear is occluded. Hearing aids, coupled with CE, occlude the external ear. Adults with BHFL may experience conflicting localization cues: that is, low-frequency cues may direct the listener to a different spatial location than the high-frequency cues. When conflicting localization cues are centrally processed, different listeners will weight them quite differently and may learn over time to rely on one cue at the exclusion of the others (Macaulay et al, 2010). As a result, CEs coupled with hearing aids can have an immediate detrimental effect on SLA in adults with BHFL by distorting acoustic cues that listeners may have exclusively used to locate sounds on the horizontal plane.

The effect of BHFL on SLA in children and the efficacy of using OFDs to improve localization performance remain unknown. No study to date has investigated this issue in young children. Nonetheless, children with unilateral hearing loss (Humes et al, 1980; Johnstone et al, 2010; Johnstone and Robertson, 2011), bilateral hearing loss (Sebkova and Bamford, 1981), deafness and cochlear implants (Litovsky et al, 2006a,b; Grieco-Calub and Litovsky, 2010; Godar and Litovsky, 2010), and normal hearing (NH) (Van Deun et al, 2009; Martin et al, 2015) have participated in sound localization studies. The findings from these studies reveal some important facts about the development of SLA. First, the auditory system requires much practice in early years to learn to localize accurately. Figure 1 shows SLA, in average root-mean-square (RMS) error (±standard deviation [SD]), for children with NH, 3–14 yr of age, reported in studies that used similar or identical methodologies to the present study. As children age, their RMS error decreases. These data support the growing body of evidence that, in humans, sound localization is a

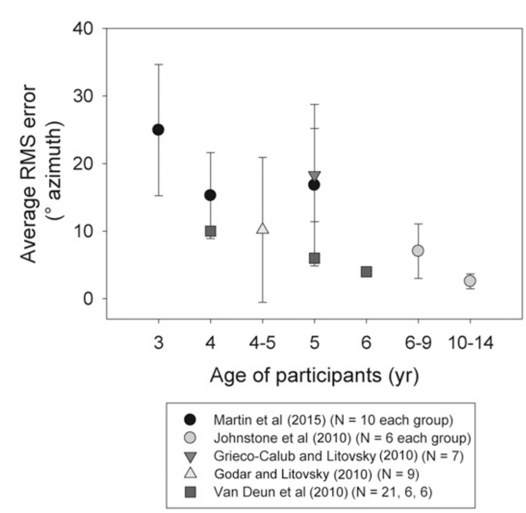


**Figure 1.** Average RMS error (±SD) is plotted as reported for groups of children (age in years) with NH in previously published studies. These studies used very similar procedures for testing SLA.

learned skill honed over the course of the first decade of life.

Second, the presence of hearing loss in children degrades localization accuracy relative to peers with NH (Humes et al, 1980; Sebkova and Bamford, 1981; Johnstone et al, 2010). However, practice over time benefits children with hearing loss just as it does children with NH. Unaided SLA improves with age in some children with impaired hearing: for example, in children with unilateral hearing loss (Johnstone et al, 2010).

Finally, prosthetic devices improve SLA in children with bilateral hearing loss when two behind-the-ear (BTE) hearing aids are used as compared to one (Sebkova and Bamford, 1981) or two cochlear implants as compared to one (Litovsky et al, 2006a,b; Johnstone et al, 2013). Prosthetic devices also improve pediatric performance on sound localization tasks over time (Johnstone et al, 2010; Zheng et al, 2015). For example, bilateral benefit for SLA was found in children with unilateral hearing loss who used a hearing aid in the impaired ear; however, the amount of benefit was significantly correlated with age at intervention (Johnstone et al, 2010). Children who received a hearing aid at a young age showed bilateral benefit, whereas children who received a hearing aid after 5 yr of age showed bilateral interference when using a hearing aid in the impaired ear. The duration of device use affects localization performance in children.

Children with BHFL pose a particular challenge to audiologists. Without published research supporting use of OFDs, audiologists are reluctant to adopt this technology for use with young pediatric patients with BHFL despite a complete lack of concern about using OFDs in adult patients with similar hearing loss configuration. The efficacy of advanced hearing aid and earmold technologies in children with BHFL remains unknown making it difficult to incorporate them into evidence-based pediatric audiology practice. Measurements of spatial hearing, such as SLA, 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 sound localization to navigate complex acoustic environments and to focus attention toward talkers of interest. One of the primary functions of the auditory system is accurate sound localization. The ability to quickly pinpoint the location of a sound source is not only critical for avoiding danger but also facilitates speech communication. Sound localization allows one to look (orient the head) toward the spatial location of a specific talker and benefit from "central gain" provided by balanced intra-aural level and timing acoustic cues. Knowing where to listen in space has been shown to significantly improve speech intelligibility for adult listeners in the presence of complex background noise and listening environments (Kidd et al, 2005; Jones and Litovsky, 2008).

The purpose of the current study is to use horizontal sound localization measurements in children 5–16 yr of age who have BHFL to compare their performance with BTE hearing aids coupled with OFDs versus CEs. The first hypothesis is that children with BHFL will show better SLA (less localization error) when using OFDs. The second hypothesis is that performance on sound localization tasks will be affected by age and duration of CE use. Finally, children with BHFL will be compared to age-matched peers with NH. The third hypothesis is that BHFL will degrade SLA in children.

## METHODS

### Participants

Children with BHFL were recruited from the pediatric patients who received services in the audiology clinic at the University of Tennessee Speech and Hearing Center in Knoxville, TN. Pediatric patients with BHFL were identified as potential participants via clinic chart review. A child was deemed eligible to participate if he or she had NH in both ears at 250 Hz, mild sensorineural loss at 500–1000 Hz, and concurrent moderate-to-severe sensorineural hearing loss at frequencies >1000 Hz. Children must have used bilateral BTE hearing aids coupled with CE for at least 4 mo prior to participation. Parents of children with BHFL were sent a letter inviting them to allow their child to participate in the study.

A total of 22 children, 5–16 yr of age, with BHFL loss were recruited. However, four children were excluded because their BTEs were older and could not be successfully retrofitted with OFDs. The remaining 18 children were divided into two age groups: older, 10–16 yr of age (N = 9, mean age 12.3 yr, SD = 1.94); and younger, 5–9 yr of age (N = 9, mean age 6.2 yr, SD = 1.48).

Table 1 provides demographic information regarding the children with BHFL including age at study participation, duration of CE usage, hearing aid make and model, prescriptive target used to fit hearing aid, signal processing/compression, microphone settings, CE style, and vent size. 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 at the start of the study.

Pure tone air and bone conduction thresholds and acoustic immitance data were obtained for each child. There was no significant difference in hearing sensitivity between the right and left ear, nor was there any significant difference in hearing sensitivity between younger and older children. Figure 2 shows the average bilateral thresholds for both age groups of children with BHFL.

An age-matched group (N = 18) of children with NH were also recruited. Children with NH were excluded if they had abnormal middle ear immitance, showed a difference in hearing sensitivity between the right and left

**Table 1. Participant Demographic Information**

| Participant Code | Sex | Age (yr) | Age (yr) Dx | Age (yr) HAs Fit | HA Use (yr) | HA Make | HA Model | Fitting Target | Signal Process | Mic Mode | Earmold Type and Vent |
|---|---|---|---|---|---|---|---|---|---|---|---|
| HLB | F | 12 | 2 | 2 | 10 | Phonak | Certena M | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |
| HLE | M | 13 | 5 | 9 | 3 | Phonak | Nios micro III | DSL child | dWDRC | Omni SF: C→SDJ | Full shell w/SAV |
| HLF | F | 13 | 5 | 5 | 9 | Phonak | Cassia microP | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |
| HLG | M | 9 | 5 | 5 | 3 | Phonak | 1.eXtra 411 AZ Forte | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |
| HLH | F | 5 | 5 | 5 | 1 | Phonak | Nios micro III | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |
| HLI | M | 7 | At birth | 7 weeks | 7 | Phonak | Nios micro III | DSL child | dWDRC | Omni SF: C→SDJ | Full shell w/2.3–3.0mm |
| HLJ | F | 6 | 9 mos | 10 mos | 5 | Phonak | Maxx 311 Forte | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/med vent |
| HLL | M | 11 | 10 | 10 | 1 | Phonak | Cassia microP | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |
| HLM | M | 12 | At birth | 1 | 11 | Phonak | eXtra 311 AZ Forte | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/.9–1.1mm |
| HLN | M | 10 | 4 | 5 | 5 | Phonak | Nios micro V | DSL child | dWDRC | Omni SF: C→SIN | Full shell w7.9–1.1mm |
| HLO | F | 5 | 5 | 5 | 4 mos | Phonak | eXtra 311 AZ Forte | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/.9–1.1mm |
| HLP | M | 8 | 6 | 6 | 2 | Phonak | Cassia microP | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |
| HLQ | M | 16 | 3 | 4 | 12 | Phonak | Certena micro | DSL child | dWDRC | Omni SF: C→SDJ | Full shell w/SAV |
| HLR | M | 6 | 4 | 4 | 3 | Phonak | Nios micro III | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |
| HLS | F | 5 | 4 | 4 | 1 | Phonak | Cassia microP | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |
| HLT | M | 5 | At birth | 6 mos | 5 | Phonak | Naida III SP dAZ | DSL child | dWDRC | Omni SF: C→SIN | Full shell w71.2–l.6nun |
| HLU | F | 10 | 3 | 3 | 7 | Phonak | Naida S III SP | DSL child | dWDRC | Omni SF: C→SDJ | Full shell w71.7–2.2mm |
| HLV | F | 14 | 3 | 3 | 11 | Phonak | Certena P | DSL child | dWDRC | Omni SF: C→SIN | Full shell w/SAV |

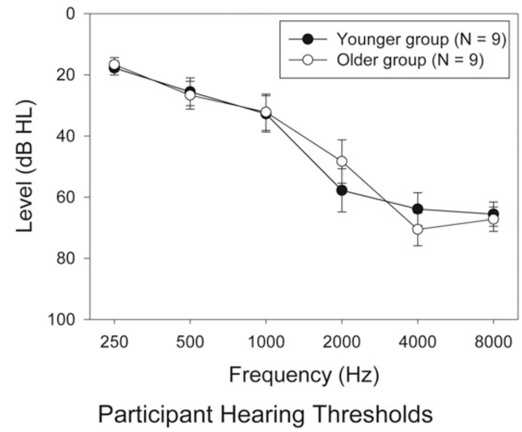


**Figure 2.** Average hearing thresholds across both ears (±SD) are plotted for the younger and older group of children with BHFL who participated in this study.

ear that was >10 dB for any frequency tested, or had hearing sensitivity >20 dB at any frequency tested between 125 and 8000 Hz in either ear. Children in the NH group were also divided into two age groups: younger, 5–9 yr of age (N = 9, mean age 7 yr; SD); and older, 10–16 yr of age (N = 9, mean age 12 yr; SD).

All children who participated in this study gave written assent to participate, and all parents or legal guardians gave written consent to have their child participate. The study was approved by the University of Tennessee Institutional Review Board.

## Test Environment and Equipment

The test environment and equipment used in the current study were identical to those reported by Johnstone et al (2010). Prior to testing, verification of hearing aid fit relative to a prescriptive target reported in the clinic chart was done using a Verifit v 1.0 real-ear measurement system for the group with BHFL for their hearing aids with their CE and another was performed with the OFD. Real ear measures were adapted to OFDs. OFDs increase the likelihood that amplified sound will leak from the open canal during the hearing aid (HA) fitting process and contaminate the mic signal during the equalization process (Lantz et al, 2007). When this happens an artificial increase in stimulus level at ear canal resonant frequencies can cause an undesirable decrease in the speech stimulus. To prevent "contamination," the sound-field equalization process was manually separated from the real ear measurements by turning off the BTE with OFD and then presenting a 1-sec broadband equalization burst. The equalization values were stored, the BTE was turned on again, and real ear measurements were made using the "carrot story" continuous speech stimulus. Both programs (one for CEs and one for OFDs) were then stored in the BTEs. Three children used hearing aids that had to be permanently retrofitted with OFDs. These children were tested unaided and with CEs randomly ordered across participants. Then their hearing aids were sent to the manufacturer to be retrofit with OFDs and they were tested a final time.

Although the BTEs were verified relative to a speech target created by a Verifit v 1.0 real-ear measurement system, the aided long-term average speech spectrum (LTASS) for the OFD and CE differed significantly from one another (see Figure 3). On average, the OFD provided ~10 dB less amplification at 500 and 750 Hz and 10 dB more amplification at 3000, 4000, and 6000 Hz as compared to the CE. However, estimated speech intelligibility index (SII) measurements provided by the Verifit system did not differ between the OFD (74 ±12) and the CE (74 ± 11) (see Figure 4). This is an important outcome, one that has also been found for adults with BHFL (Alworth et al, 2010).

Testing was conducted in a sound-treated booth (IAC Acoustics, 2.2 × 1.8 m; North Aurora, IL). Participants sat at a small padded chair-style desk facing a semicircular array of 15 loudspeakers (Cambridge SoundWorks Center/Surround IV [Creative Labs, Milpitas, CA]; matched within 1 dB at 100–8000 Hz) placed at 10° intervals on an arc (with a radius of 1 m) between 270° and 70° azimuth. A small picture was attached under each loudspeaker. These pictures corresponded to an arc of pictures displayed on a computer screen after each trial. One trial consisted of a single presentation of the word "baseball." Hardware including a Tucker Davis Technologies (Alachua, FL) System III (RP2, PM2, AP2), in conjunction with a Dell OptiPlex 9020 (Round Rock, TX) 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.

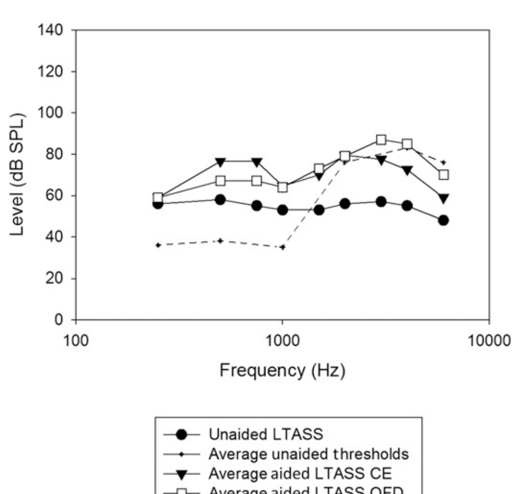


**Figure 3.** The average aided (OFD) LTASS is shown relative to the unaided LTASS, average aided (CE), and unaided average hearing thresholds for the children with BHFL.

### Stimuli

The stimuli consisted of a single word, the spondee "baseball," digitally recorded with a male voice at a sampling rate of 44.1 kHz, RMS equalized, and stored as a .wav file. The level of the stimuli was calibrated to 60 dB SPL and randomly varied on a trial-by-trial basis between 52 and 68 dB SPL (roved ±8 dB). The word "baseball" was used for several reasons: first, this convention was used in other seminal published studies (e.g., Litovsky et al, 2006a,b; Johnstone et al, 2010; Johnstone and Robertson, 2011; Johnstone et al, 2013; Martin et al, 2015) and by using it again in the current study one might better compare findings across studies. Second, it contains high-frequency and low-frequency acoustic cues both of which contribute to SLA. Finally, no picture of a baseball was included in the pictures that participants selected to identify the location of the loudspeaker from which the word "baseball" originated during the experiment (see "Sound Source Identification Procedure" section).

### Experimental Conditions

All testing was done using a "listening game" format with interactive computer software to engage the child to keep on task (Johnstone et al, 2010). During individual trials, the child was reminded to orient his or her head toward 0° azimuth. If noticeable head movement occurred, the data for that trial was discarded and an additional trial was presented.

A total of three experimental conditions were tested with children with BHFL. Experimental conditions consisted of sound source identification without amplification, with CEs, and with OFDs. The order of these conditions randomly varied across participants with BHFL. Children with NH were tested once.

### Sound Source Identification Procedure

The child sat in an appropriately sized, padded chair-style, classroom desk facing a loudspeaker at 0° azimuth below which a small flat computer screen was located. On the desktop, a computer mouse and mouse pad were placed. The child was told to face forward, remain still during the trial, and look at the computer screen. A single trial consisted of the presentation of the word "baseball." Each loudspeaker had a different small picture below it. The child was 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 believed to have originated. If the child was too young or was unable to control the mouse, the child verbally reported the picture and the investigator clicked on the picture that the child indicated (four

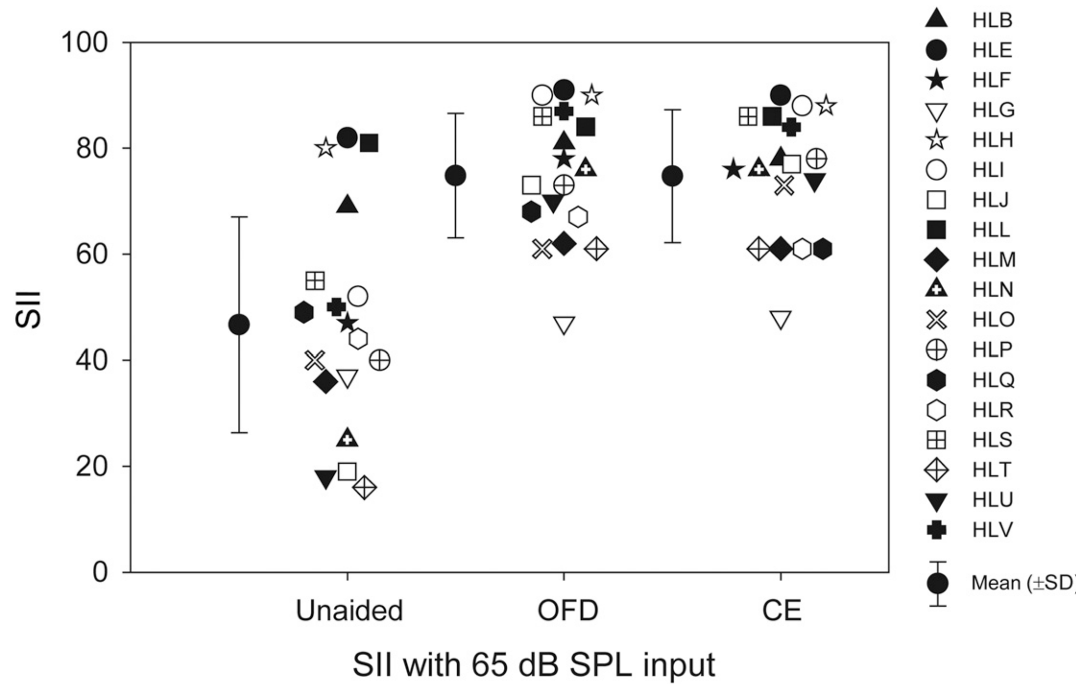


**Figure 4.** Estimates of the SII as computed by the Verifit system at 65 dB SPL input are plotted for each individual child with BHFL. Both OFD and CE improve the SII relative to unaided. The SII value was identical to OFD and CE.

6-yr-old children required that the investigator control the mouse). After each response, feedback was provided such that the correct-location icon flashed on the computer screen as has been used in previous studies (Johnstone et al, 2010; Johnstone et al, 2013). In addition, a puzzle picture appeared piece by piece after each response. The stimulus, "baseball," was randomly presented a total of 10 times to each of the 15 loudspeakers for a total of 150 trials per experimental condition. Children were rewarded with prizes and stickers after every 25 trials.

## RESULTS

In Figure 5, group average RMS error (±SD) for children with BHFL is plotted. No main effect for amplification or child age was found. However, there was a statistically significant (amplification × child age) interaction [$F_{(2,32)} = 5.817$, $p < 0.01$]. Post hoc repeated measures analysis of variance (ANOVA) revealed a statistically significant main effect for listening mode (unaided versus CE versus OFD) for younger children with BHFL [$F_{(2,16)} = 4.52$, $p < 0.05$] but not for older children with BHFL. Post hoc paired-sample $t$-tests revealed that in younger children with BHFL, localization accuracy was statistically significantly better with the OFDs as compared to unaided performance [$t_{(8)} = 2.609$, $p < 0.05$]. There was no difference between unaided localization accuracy and that obtained with CEs.

Post hoc one-way between groups ANOVA revealed that younger children with BHFL demonstrated significantly poorer localization accuracy (higher mean RMS error) than older children with BHFL when unaided [$F_{(1,16)} = 17.048$, $p < 0.001$] and when using CEs [$F_{(1,16)} = 6.454$, $p < 0.05$]. There was no statistically significant difference between age groups when OFDs were used. As hypothesized, chronological age affected SLA. However, the difference in performance between age groups was no longer significant when both groups used OFDs. That is because children in the younger age group showed a significant improvement in SLA when

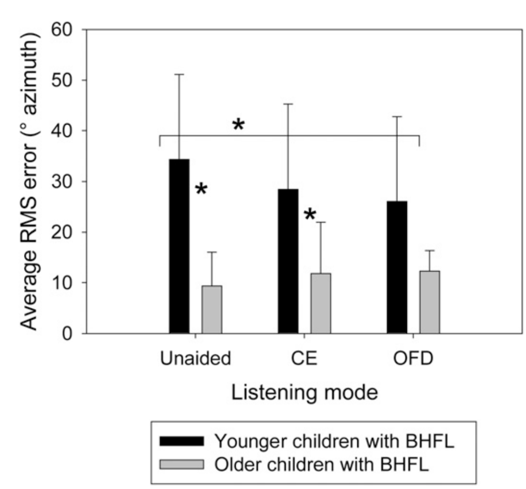


**Figure 5.** Average localization error (±SD) for younger and older children with BHFL is plotted for each listening condition (unaided, CE, OFD). Asterisks indicate listening conditions where a significant difference was found between or within groups.

using OFDs when compared to unaided [$t_{(8)} = 2.609$, $p < 0.05$] and the performance of older children remained the same across listening conditions (unaided, CEs, OFDs).

Figure 6 shows the relationship between duration of CE use on immediate benefit using OFDs in children with BHFL. Immediate benefit using OFDs was calculated by subtracting OFD-aided RMS error from unaided RMS error for each child. The open symbols represent individual children in the younger age group, and the filled symbols represent children in the older age group. The horizontal dotted line at zero refers to values with no OFD advantage or disadvantage. Symbols that fall above the dotted line show OFD advantage (OFD-aided RMS error was smaller than unaided), and symbols that fall below the dotted line show OFD disadvantage (OFD-aided RMS error was larger than unaided). There was a statistically significant negative correlation between the duration of CE usage and the amount of immediate bilateral benefit when using OFDs ($r = -0.634$, $p < 0.005$). When the duration of CE use was <6 yr, children with BHFL typically showed immediate benefit when using OFD, whereas when the duration of CE use was >6 yr, children with BHFL showed immediate interference with the OFDs. As hypothesized, OFDs offered immediate benefit to children with BHFL. However, this immediate benefit was found only for children who had used CEs for <6 yr.

Regardless of chronological age, when children with BHFL were fit with the OFDs they often made immediate comments to their accompanying parent and/or the researchers about the difference of the sound of their hearing aids with the OFDs. A spontaneous (completely unsolicited), immediate improvement in own-voice quality was reported by 94% (17/18) of the participants.

When children with BHFL (without amplification) were compared to age-matched children with NH, a statistically significant main effect was found for hearing loss [$F_{(1,32)} = 30.361$, $p < 0.0005$] and age [$F_{(1,32)} = 20.836$, $p < 0.0005$] (see Figure 7). In addition, a statistically significant (group × age) interaction was found [$F_{(1,32)} = 10.654$, $p < 0.005$] (see Figure 8). As hypothesized, the presence of BHFL in children degrades SLA. Post hoc one-way ANOVAs showed that children in the younger BHFL group, however, had statistically significant larger sound localization error than older children with BHFL [$F_{(1,16)} = 17.048$, $p < 0.001$], younger children with NH [$F_{(1,16)} = 21.868$, $p < 0.0005$], and older children with NH [$F_{(1,16)} = 31.59$, $p < 0.0001$]. Younger children with NH also showed statistically significant greater sound localization error than older children with NH [$F_{(1,16)} = 4.899$, $p < 0.05$]. As hypothesized, younger children, regardless of hearing ability, showed significantly greater localization error than older children.

## DISCUSSION

The results of this study revealed that some children with BHFL show immediate improved SLA when using OFDs. Aided benefit was best predicted by the duration (in years) of use of CE. Children who had used hearing aids with CE for <6 yr showed immediate

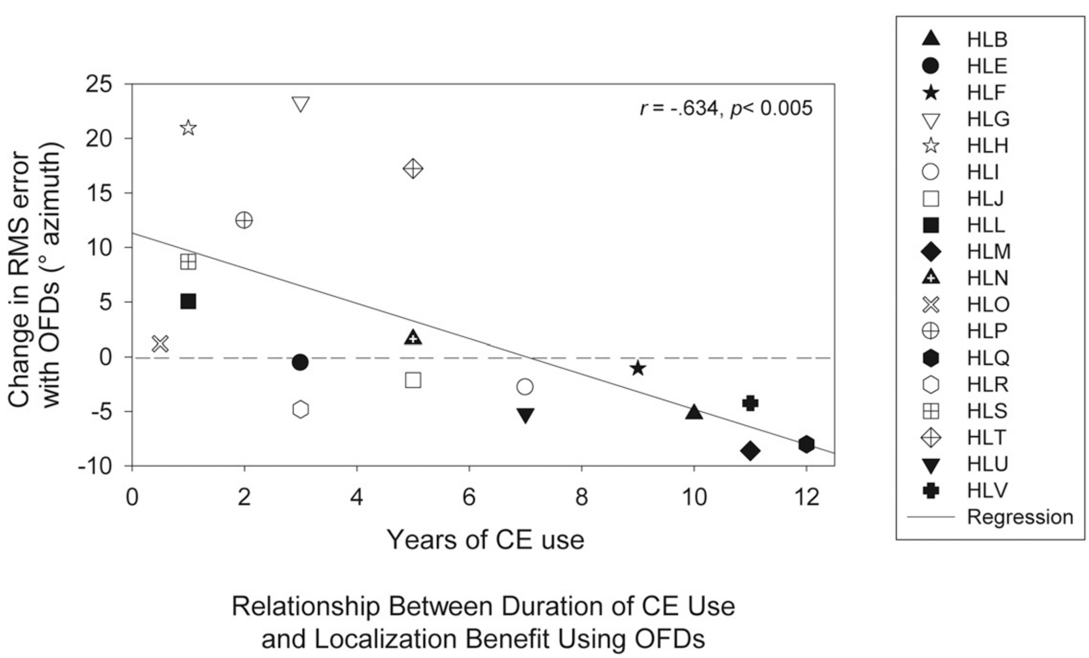


**Figure 6.** The change in localization error when using OFDs is plotted for each child with BHFL. Children in the older age group are represented by filled symbols. The dashed horizontal line indicates no change. Symbols that fall above the dashed line indicate immediate improvement in localization error with OFDs and symbols that fall below the dashed line indicate immediate worsening of localization error with OFDs.

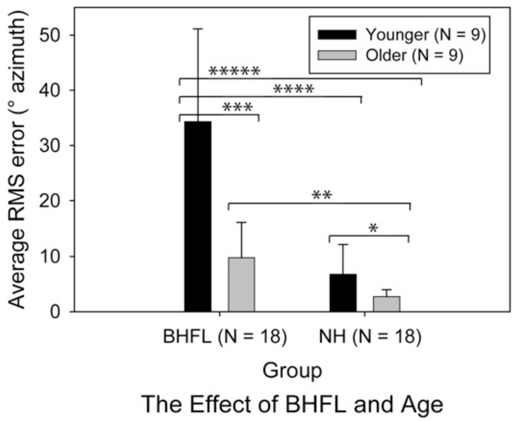


**Figure 7.** Average localization error (±SD) is plotted for younger and older children with BHFL and children with NH. Asterisks indicate post hoc comparisons that were significantly different (* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.005$; **** = $p < 0.001$; ***** = $p < 0.0005$).

improvement in SLA with the OFDs. Immediate interference in SLA was seen in children who had used CE for >6 yr. Younger children (5–9 yr of age) typically showed immediate benefit in SLA when using OFDs.

Evidence in the current study implicated developmental factors may also play an important role in improving SLA over time for children with BHFL. Without hearing aids, the older children with BHFL had significantly better SLA than younger children with BHFL regardless of the duration of CE use. In other words, localization accuracy appeared to improve with chronological age. This improvement in unaided and aided SLA over time might be explained by children learning to rely on a specific set of acoustic cues while gradually ignoring others.

One cannot, however, be certain of developmental effects without additional studies. Future studies should include several features. First, longitudinal aided and unaided localization data for young children with BHFL should be obtained. Follow-up over a 5-yr period during early childhood could help elucidate the interplay between development and amplification in SLA. Second,

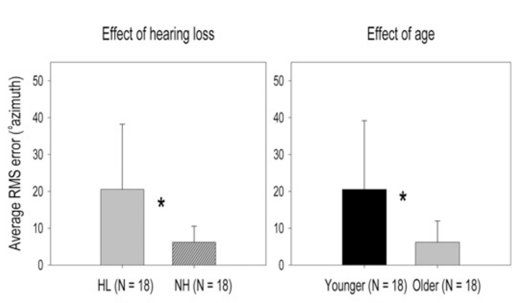


**Figure 8.** Average localization error (±SD) is plotted to show the effect of BHFL and age. Asterisks indicate a significant difference between groups.

children who were identified at birth with BHFL and fit with hearing aid amplification before their first birthday should be included in studies if possible. In the current study, we found a relationship between immediate benefit using OFDs and shorter duration of CE use. It seems important to determine whether greater benefit will occur with even earlier use of OFDs, particularly since audiologists tend to not recommend OFDs for infants, toddlers, or young school-age children with BHFL.

Finally, the occlusion effect with regard to earmold selection is poorly understood in children. We do know, however, from adult patients that earmolds with insufficient venting act like amplifiers for trapped, low-frequency, osseotympanic sounds that creates an unpleasant own-voice, "head-in-a-barrel" sensation (Kuk et al, 2005). Models of the occlusion effect show that smaller ear canal volume is associated with larger trapped, low-frequency SPL in the ear canal (Stenfelt and Reinfeldt, 2007). This would suggest that young children with BHFL, who would typically have smaller car canal volumes than adults, could experience considerable distortion of their own voice when using CEs with their hearing aids—even though they rarely complain of this problem. Support for this assumption was serendipitously found in the current study; 94% (17/18) of the children with BHFL spontaneously reported an immediate improvement in own-voice quality when using the OFDs during the study. It seems likely that the occlusion effect impacts young children far more than currently appreciated and certainly warrants further investigation.

## CONCLUSIONS

OFDs can provide sound localization benefit to young children with BHFL. However, immediate benefit from OFDs is reduced by prolonged use of CEs. Although developmental factors may play a role in improving localization abilities over time for children with BHFL, children with BHFL will rarely equal the ability of peers without early use of minimally disruptive HA technology. It is also likely that the occlusion effect impacts children far more than currently thought.

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