Research Article

Audibility-Based Hearing Aid Fitting Criteria for Children With Mild Bilateral Hearing Loss

Ryan W. McCreery,^a Elizabeth A. Walker,^b Derek J. Stiles,^c Meredith Spratford,^a Jacob J. Oleson,^d and Dawna E. Lewis^a

Purpose: Because of uncertainty about the level of hearing where hearing aids should be provided to children, the goal of the current study was to develop audibility-based hearing aid candidacy criteria based on the relationship between unaided hearing and language outcomes in a group of children with hearing loss who did not wear hearing aids.

Method: Unaided hearing and language outcomes were examined for 52 children with mild-to-severe hearing losses. A group of 52 children with typical hearing matched for age, nonverbal intelligence, and socioeconomic status was included as a comparison group representing the range of optimal language outcomes. Two audibility-based criteria were considered: (a) the level of unaided hearing where unaided children with hearing loss fell below the median for children with typical hearing and (b) the level of unaided

hearing where the slope of language outcomes changed significantly based on an iterative, piecewise regression modeling approach.

Results: The level of unaided audibility for children with hearing loss that was associated with differences in language development from children with typical hearing or based on the modeling approach varied across outcomes and criteria but converged at an unaided speech intelligibility index of 80.

Conclusions: Children with hearing loss who have unaided speech intelligibility index values less than 80 may be at risk for delays in language development without hearing aids. The unaided speech intelligibility index potentially could be used as a clinical criterion for hearing aid fitting candidacy for children with hearing loss.

Although there is professional agreement that children with moderate or greater degrees of hearing loss should receive amplification at the earliest possible age, there is a lack of a consensus among scientists and clinicians about the amplification needs of children with milder degrees of hearing loss. Mild bilateral hearing loss (MBHL) is defined as average audiometric pure-tone

thresholds between 26 and 40 dB HL (Clark, 1981) in both ears. Previous research suggests that children with MBHL may be at risk for delays in communication and academic development (see Tharpe, 2008, for a review). Although most universal newborn hearing screening protocols are not intended to identify degrees of hearing loss less than 35–40 dB HL (Norton et al., 2000), a subset of children with MBHL are identified through newborn hearing screening (Holte et al., 2012). The early identification of infants with MBHL requires audiologists to make decisions about the appropriate intervention approach, including whether hearing aids should be fitted. A recent literature review by Winiger, Alexander, and Diefendorf (2016) highlighted inconsistent practices related to the provision of amplification for children with MBHL. The dearth of evidence-based hearing aid candidacy guidelines for children with MBHL contributes to inconsistency in whether children in this population receive hearing aids or at what age (Grandpierre, Fitzpatrick, Na, & Mendonca, 2017; Walker, Holte, et al., 2015). The ambivalence about hearing aid provision for children with MBHL also leads to confusion among parents about whether hearing aids are an appropriate

^aAudibility, Perception and Cognition Laboratory, Boys Town National Research Hospital, Omaha, NE

^bDepartment of Communication Sciences and Disorders, The University of Iowa, Iowa City

^cAudiology Program, Boston Children's Hospital, MA

^dDepartment of Biostatistics, The University of Iowa, Iowa City

Correspondence to Ryan W. McCreery:

Ryan.McCreery@boystown.org

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intervention for their child (Fitzpatrick, Durieux-Smith, Gaboury, Coyle, & Whittingham, 2015). In an effort to support more consistent provision of amplification for children with MBHL, the goal of this study was to examine the relationship between unaided hearing levels and language outcomes in order to develop an evidence-based hearing aid candidacy criterion for children with MBHL.

The Effects of MBHL on Developmental Outcomes

Prior to universal newborn hearing screening and early intervention programs, studies suggested that at least some school-age children with MBHL had deficits in language, academic, and psychosocial skills compared to peers with typical hearing (Bess, Dodd-Murphy, & Parker, 1998; Davis, Elfenbein, Schum, & Bentler, 1986; Wake, Hughes, Collins, & Poulakis, 2004). MBHL during childhood has been associated with delays in developmental domains including language (Tomblin et al., 2015; Walker, Holte, et al., 2015), morphosyntax (Koehlinger, Van Horne, Oleson, McCreery, & Moeller, 2015), phonological awareness (Briscoe, Bishop, & Norbury, 2001), and speech recognition in noise (Crandell, 1993; Hawkins, 1984; McCreery et al., 2015). However, a population-based cohort examined by Wake et al. (2006) found that children with MBHL ($n = 55$) did not differ from peers with typical hearing in language, reading, behavior, or ratings of quality of life. Mixed findings across previous studies have left unanswered questions about whether children with mild hearing loss are at risk for delays in communication and other areas of development.

The benefits of early identification of hearing loss and hearing aid provision for children with MBHL are also unclear. The Longitudinal Outcomes of Children with Hearing Impairment study in Australia did not find a benefit of earlier age of amplification for language abilities among children with MBHL at 3 years of age (Ching & Dillon, 2013). This finding was taken as evidence that children with milder degrees of hearing loss may have sufficient residual hearing to support typical communication development. A recent investigation of language outcomes for children with varying degrees of hearing loss found no advantage for children with MBHL who were identified through universal newborn hearing screening compared to children with MBHL who received later identification of hearing loss and intervention (Carew et al., 2018). The authors concluded that MBHL may represent a problem of overdiagnosis of hearing loss rather than a real developmental risk because of the lack of evidence of benefit from early identification of hearing loss and subsequent intervention. However, the potential for developmental delays in children with MBHL observed in many other studies suggests that our current methods of determining hearing aid and intervention candidacy in children may be insufficient for differentiating children who are at risk for delays from peers who may have sufficient hearing to develop speech and language without intervention.

Inconsistent findings in the literature regarding the benefits of intervention for children with MBHL have led to inconsistent clinical practices and intervention

recommendations for this population. Fitzpatrick, Whittingham, and Durieux-Smith (2014) found that amplification was only recommended for 58% of children with MBHL within 3 months of identification of hearing loss. Within 12 months of identification, approximately 87% of children in their study had received a recommendation for amplification. This delay in recommending amplification likely reflects the uncertainty of audiologists in recommending amplification when infants and young children present with MBHL. Even when amplification is recommended for children with MBHL, establishing consistent hearing aid use can be challenging. Cross-sectional (Walker et al., 2013) and longitudinal (Walker, McCreery, et al., 2015) studies of hearing aid use suggest that children with MBHL wear their hearing aids for fewer hours per day on average than do peers with greater degrees of hearing loss, though there is considerable individual variability in hearing aid use. Similarly, results from the previously cited Fitzpatrick et al. study found that only 70% of children who were recommended to receive hearing aids wore them consistently based on parent report. Inconsistent recommendations for amplification combined with variable hearing aid use among children with MBHL limit the potential benefits of early identification of hearing loss. Furthermore, inconsistent access to and use of amplification among children with MBHL makes it difficult to assess whether MBHL represents a developmental risk and whether hearing aids are an effective intervention.

Another challenge in developing cohesive conclusions regarding the developmental effects of MBHL is the tendency for previous studies to combine the results of children with MBHL with children with varying degrees of unilateral hearing loss under the umbrella term of minimal hearing loss (Bess et al., 1998; Fitzpatrick et al., 2014; Lewis, Valente, & Spalding, 2015; Porter, Sladen, Ampah, Rothpletz, & Bess, 2013; Tharpe, 2008). These groups have often been combined because children with mild bilateral and unilateral hearing losses show similar patterns of variable developmental and academic outcomes across studies. Children in each of these groups often do not receive consistent recommendations regarding the need for amplification (Fitzpatrick et al., 2014; Kochkin, Luxford, Northern, Mason, & Tharpe, 2007). However, combining these groups together makes it difficult to differentiate potential interventions for each condition. For example, children with MBHL have a loss of audibility for soft speech sounds that can be largely compensated for with amplification. Conversely, children with unilateral hearing loss have altered or absent binaural hearing cues due to their asymmetrical hearing between ears. Unlike MBHL, restoration of audibility for binaural cues with amplification may not lead to coherent representations of these cues in cases of severe or profound unilateral hearing loss. For the purposes of developing amplification candidacy guidelines, different hearing aid candidacy criteria are likely to be needed for children with MBHL compared to children with unilateral hearing losses.

Current Amplification Candidacy Criteria for Children With MBHL

Although there has been a history of research documenting the potential developmental risks of MBHL, there has not been coherent guidance in clinical guidelines or protocols about the degree of hearing loss where amplification is routinely recommended. The standard for defining mild hearing loss for children in previous studies and clinical guidelines has been based on audiometric thresholds in dB HL or estimates of audiometric thresholds from auditory brainstem response assessment in dB nHL. The dB HL scale was developed as the standard for hearing level for the audiogram because normal levels of human hearing in dB SPL are different at each frequency. The average threshold level for a group of adults with normal hearing is set to 0 dB HL. The dB nHL scale is used to represent sound levels measured with brief duration stimuli used for auditory brainstem response measures. Both dB HL and dB nHL are used to relate hearing levels to dB SPL measured in a coupler designed to represent an average adult ear canal volume. Although these scales are used to represent degree of hearing loss on the audiogram, clinical guidelines rarely specify an audiometric level of hearing for hearing aid fitting for children with MBHL. The American Academy of Audiology (2013) Pediatric Amplification Guideline suggests that children with MBHL may be at risk for developmental and academic delays and should be considered candidates for hearing aids, but it does not propose a hearing level where hearing aids should be fitted. The Ontario Infant Hearing Program: Protocol for the Provision of Amplification (Ontario Ministry of Children and Youth Services, 2014) and the Australia Hearing Amplification Protocol (King, 2010) also do not set a specific audiometric criterion for hearing aid candidacy for children with MBHL.

There are several factors that have contributed to the lack of specific dB HL audiometric criteria for hearing aid candidacy. Children with the same audiometric degree of hearing loss often have heterogeneous outcomes. As Tharpe (2008) points out in a review of the literature on unilateral hearing loss and MBHL, the considerable variation in outcomes among children with the same degree of hearing loss presents challenges for clinicians in deciding when children should receive intervention. Some children who are diagnosed with MBHL do not exhibit developmental differences from children with normal hearing, even without the provision of hearing aids or intervention (e.g., Fitzpatrick et al., 2015; Wake et al., 2006). Evidence about the level of hearing where developmental risks consistently arise could provide important guidance for developing more consistent amplification guidelines. Despite the lack of agreement regarding hearing aid candidacy criteria for children with MBHL, clinical audiologists have developed at least two management strategies for this population that are evident from the research: a “failure-based approach” (described by Winiger et al., 2016) and an audiometric approach.

The failure-based approach to management of children with MBHL involves waiting to provide amplification

or other intervention until delays in communication are observed. Since there are children with MBHL who seemingly do not exhibit developmental delays, fitting only those children who exhibit deficits could be considered an efficient method of only providing amplification in cases where there is evidence that hearing aids are needed. Although audiologists are unlikely to characterize their approach to fitting hearing aids for children with MBHL in this manner, the pattern of inconsistency of the provision and delayed timing of amplification in children with MBHL suggests professional uncertainty exists about the potential developmental risks of MBHL and benefits of amplification. In several studies (Fitzpatrick et al., 2014; Walker et al., 2014), amplification was not recommended initially for children with MBHL. The likelihood of amplification provision increased as children grew older and developmental risks started to emerge. The main limitation of a failure-based model is that it requires the child to fall behind their peers with normal hearing before intervention is provided. This means that some children who could benefit from amplification may experience developmental delays that would be preventable if amplification had been provided.

The audiometric approach to hearing aid candidacy uses audiometric thresholds as the precondition for amplification. Because there is no recommended audiometric benchmark for providing hearing aids, individual audiologists vary in the specific audiometric criteria that they use. This practice pattern is evident from a study by Walker, Holte, et al. (2015) of the developmental outcomes of a group of children with mild hearing loss from across the United States. Some children with MBHL had a recommendation for amplification, and some did not, despite having similar audiometric thresholds. A key predictor of the audiologists’ recommendations regarding amplification was the child’s better-ear pure-tone average (BEPTA) from the audiogram. For a 20-dB HL BEPTA, less than half of the children received a recommendation for amplification, but as the threshold moved closer to 30 dB HL, the proportion of children for whom amplification was recommended approached 100%. Audiologists have developed their own standard of fitting amplification for children with MBHL that typically falls somewhere between 20 and 30 dB HL. The challenge with the audiometric approach is that it lacks standardization, and a child with mild hearing loss may or may not receive amplification depending on the individual criterion used by the audiologist they happen to see.

There are also limitations of using the dB HL audiogram as the standard for hearing aid candidacy in infants and children. For insert earphones or earmolds, which are the recommended couplings for hearing assessment of infants and young children, the effective sound level in the ear canal of an infant or child is typically higher than the sound level in the 2-cm³ coupler on which the dial reading for the audiometric equipment is calibrated. This difference between the presumed calibrated (dB HL or dB nHL) level of the audiometric equipment and the level in the ear canal (dB SPL) is known as the real-ear-to-dial difference (Munro & Davis, 2003; Munro & Lazenby, 2001). The real-ear-to-dial

difference for infants and children can be considerable because their ear canals are smaller than the coupler used for audiometric calibration. The result of the higher effective sound level in the infant's or child's ear canal is the clinical impression of better thresholds when referenced to dB HL. Children who appear to have MBHL on the dB HL audiogram may actually have poorer hearing thresholds when the influence of ear canal acoustics is taken into consideration. The other potential negative consequence of the dB HL reference for children is that, as the child's ear canal grows over time, the threshold in dB HL will increase as the effective sound level in the ear canal decreases, even if the child's auditory function does not change. Figure 1 shows the hearing thresholds for children with a flat MBHL at two different ages. Note that the unaided audibility is poorer for the younger child than that of the older child after the influence of ear canal acoustics on the insert earphone coupling on thresholds is taken into account by converting the thresholds to dB SPL.

Consideration of the effects of individual ear canal acoustics on audiometric thresholds measured with insert earphones or earmolds for children has been recommended as part of the Desired Sensation level amplification fitting method for many years (Scollie et al., 2005), but this approach has rarely been applied to decisions about hearing aid candidacy for several reasons. As noted previously, studies of the effects of hearing loss have traditionally been referenced to the dB HL audiogram. Adjusting dB HL thresholds to account for individual ear canal acoustics might provide more individualized estimates of thresholds, but alone would not provide consistent hearing-aid candidacy criterion for children with MBHL. An ideal hearing aid candidacy criterion for MBHL not only should account for individual differences in ear canal acoustics but also should allow professionals and parents to assess the impact of hearing loss on communication and the child's developmental potential.

An alternative approach to the dB HL audiogram would be to convert the child's thresholds to dB SPL in the ear canal and estimate the impact of the child's thresholds on speech audibility using the speech intelligibility index (SII; American National Standards Institute, 1997). The SII is a standardized measure that quantifies the proportion of the long-term average speech spectrum that is audible under specific listening conditions for each ear. The SII can be used to quantify speech audibility either with a hearing aid (aided SII) or without (unaided SII). To date, the SII primarily has been used to predict speech recognition for adults (Soli et al., 2018; Studebaker, Pavlovic, & Sherbecoe, 1987; Studebaker & Sherbecoe, 1991) and children (McCreery & Stelmachowicz, 2011; Scollie, 2008). More recently, the aided SII has been used to quantify a child's auditory access over time and has emerged as an important predictor of communication outcomes in children with mild-to-severe hearing loss (McCreery et al., 2015; Stiles, Bentler, & McGregor, 2012; Tomblin et al., 2015; Tomblin, Oleson, Ambrose, Walker, & Moeller, 2014). The predictive value of the aided SII for children with hearing loss supports the notion that a criterion for hearing aid candidacy based on the degree to which unaided audibility is reduced by hearing loss could be more informative than audiometric threshold in dB HL. A hearing aid candidacy criterion based on the unaided SII avoids the limitations of the dB HL audiogram related to a lack of consideration of ear canal acoustics but also allows for quantification of the child's access to communication.

Whereas the concept of using the aided SII for cochlear implant candidacy has been suggested (Leal, Marriage, & Vickers, 2016), the implementation of the unaided SII as a candidacy criterion for hearing aids is limited by the current lack of evidence about the degree of hearing loss where delays in speech and language begin to emerge across the range of degrees of hearing loss. The goal of this study was

Figure 1. Comparison of hearing thresholds in dB SPL for a 3-month-old (left) and 6-year-old (right) with the same mild degree of hearing loss based on the audiogram (30-dB HL thresholds at 0.5–4 kHz). Once the effect of ear canal acoustics on thresholds has been modeled by converting the dB HL thresholds to dB SPL, the 3-month-old has a lower unaided speech intelligibility index (SII) than the 6-year-old due to poorer hearing thresholds. RMS = root-mean-square average speech level; Thresh = hearing threshold in dB SPL.

to assess different criteria for hearing aid candidacy based on the unaided SII. To determine the level of unaided speech audibility where the risk of developmental delays occurred, language and speech recognition outcomes were assessed for a subset of children from the Outcomes of Children with Hearing Loss (OCHL) study (Moeller & Tomblin, 2015) who did not receive hearing aids or received hearing aids and did not use them. Children with a range of degrees of hearing loss were included in the analysis for two reasons. First, including children with varying degrees of hearing loss allows for a more complete assessment of the relationship between unaided hearing and language outcomes than would be possible if only children with mild degrees of hearing loss were included. Second, including only children with mild degrees of hearing loss based on the audiogram would have contradicted a key motivation for the study that mild hearing loss in children represents a wider range of hearing losses once the influence of ear canal acoustics is taken into consideration. The effect of unaided SII on these outcomes, combined with the comparison of these outcomes to a group of children with typical hearing matched for age, socioeconomic status (SES), and nonverbal intelligence, was used to determine what level of unaided audibility served as a cut-point for risks for communication development. Based on these results, a clinical criterion for amplification based on the unaided SII could be developed for clinical use.

Method

Participants

Fifty-two children (32 boys, 20 girls) with hearing loss who were a subsample of the longitudinal OCHL study contributed data to this analysis. The inclusion criteria for the OCHL study were as follows: (a) permanent, bilateral hearing loss of mild-to-severe degree (< 80 -dB HL BEPTA); (b) no known developmental conditions or diagnoses at the time of enrollment in the study; and (c) spoken English as the primary language of the home. The subsample included in this analysis had the additional inclusion criterion that they either did not receive a hearing aid or received a hearing aid and had less than 4 hr of use per day on average based on parent report or hearing aid data logging. Forty-one of the children received a hearing aid at some point during the study (mean BEPTA = 39.9 dB HL), and 11 children did not receive a hearing aid (mean BEPTA = 23.6 dB HL). The data were collected at 94 study visits, where the children were between 3 and 10 years of age. A group of 52 children with typical hearing from the OCHL cohort matched for age, SES, and nonverbal intelligence were included as a comparison for each of the language outcome measures. Participants contributed multiple visits for the analysis across different language outcome measures. If a measure was repeated across study visits, only the child's data from the first study visit were included for that measure. Table 1 shows the demographic characteristics of the study participants.

Materials

Audiological and Hearing Aid Measures

Otосcopy was completed to ensure each ear canal was clear. Tympanometry was conducted to document middle ear status. Pure-tone audiometric thresholds for octave frequencies from 0.25 to 8 kHz were measured at each study visit in a sound-treated audiometric test booth or a sound-treated mobile van by a pediatric audiologist using age-appropriate behavioral techniques. Air-conduction thresholds were measured with ER-3A insert earphones with foam tips or TDH-50 circumaural headphones. Pure-tone air-conduction thresholds for each child were used to generate an unaided SII (American National Standards Institute, 1997) for each ear for an average speech signal (65 dB SPL). To calculate the unaided SII, audiometric thresholds in dB HL were converted to dB SPL by adding the reference equivalent thresholds for SPL and real-ear-to-coupler difference (RECD) for the transducer used for the assessment. Each child's measured RECD was used for estimating unaided SII whenever possible, and an age-based average RECD was used only if it was not possible to measure the RECD. Hearing aid use was documented using data logging from the hearing aid ($n = 35$) or parent report ($n = 47$) from a hearing aid questionnaire (described by Walker et al., 2013, and Walker, McCreery, et al., 2015). When both data logging and parent report were available, there was good agreement ($r = .79$, $p < .0001$), so data logging was used to document average hours of hearing aid use for those cases.

Language Measures

Three standardized measures of language were selected to assess the effects of limited or no amplification use. If fitted with amplification, children wore hearing aids during the language tests. The Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4; Dunn & Dunn, 2007) was completed as a measure of receptive vocabulary at the 5-, 7-, or 9-year visits for children in the OCHL study or the first- and third-grade visits for the continuation study. The PPVT-4 requires the child to point to a picture that matches a verbally presented word from a set of four items of increasing difficulty. The Vocabulary subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Psychological Corporation, 1999) was used to measure expressive vocabulary skills. The WASI Vocabulary subtest requires the child to verbally describe a word presented. The WASI Vocabulary subtest was given between the ages of 5 and 9 years for the OCHL study and at first, second, third, or fourth grade in the continuation study. The Syntax Construction subtest of the Comprehensive Assessment of Spoken Language (CASL; Carrow-Woolfolk, 1999) was used to measure knowledge and use of expressive grammar. In the CASL Syntax Construction task, the child must complete a sentence presented verbally by the examiner using syntactically and semantically appropriate words or phrases with a visual picture cue. The CASL Syntax Construction subtest was completed at study visits when the children were between the ages of 3 and 8 years. The PPVT-4 and CASL have a mean standard score of 100 with an *SD*

Table 1. Demographic characteristics of participants.

Hearing group	Children with hearing loss (<i>n</i> = 52)	Children with typical hearing (<i>n</i> = 52)
Sex	Male = 32, female = 20	Male = 27, female = 25
Maternal educational level	<i>M</i> = 15.1 years of education Range: 9–24	<i>M</i> = 15.5 years of education Range: 9–24
Age	<i>M</i> = 6.6 years Range: 3–10 years	<i>M</i> = 6.7 years Range: 3–10 years
Age of identification of hearing loss	<i>M</i> = 15.5 months <i>Mdn</i> = 1 month Range: 0–84 months	
Age of confirmation of hearing loss	<i>M</i> = 24 months <i>Mdn</i> = 16 months Range: 0–84 months	
Better-ear PTA	<i>M</i> = 36.4 dB HL <i>Mdn</i> = 36.2 dB HL Range: 6.25–73 dB HL	
Better-ear degree of loss by audiometric category	Normal (0–20 dB HL) = 12 Mild (20–44 dB HL) = 22 Moderate (45–69 dB HL) = 15 Severe (> 70 dB HL) = 3	
BEUSII	<i>M</i> = 54.3 <i>Mdn</i> = 54 Range: 5–100	
Children with hearing aids (<i>n</i> = 41)		
Age of HA fit	<i>M</i> = 23 months <i>Mdn</i> = 16.5 months Range: 1.5–66 months	
Aided SII	<i>M</i> = 80.5 <i>Mdn</i> = 82 Range: 29–98	
HA use	<i>M</i> = 2.4 hr/day <i>Mdn</i> = 2.3 hr/day Range: 0–4 hr/day	

Note. PTA = pure-tone average; BEUSII = better-ear unaided speech intelligibility index; HA = hearing aid; SII = speech intelligibility index.

of 15, whereas the WASI Vocabulary subtest has a mean *t* score of 50 with an *SD* of 10.

Statistical Method

All statistical analyses were conducted using R Version 3.4.4 (R Core Team, 2018). To assess the effects of unaided hearing levels on language outcomes, two separate statistical approaches were used. The first method was based on the median for children with typical hearing on each of the language measures. A linear regression model for participants with hearing loss was constructed with unaided SII as a predictor of the language outcome. The better-ear unaided SII (BEUSII) value where the linear regression line intersected the median for children with typical hearing on each measure was used to identify the criterion for the level of unaided audibility where children with hearing loss achieved language scores on par with those of children with typical hearing. The second method used piecewise regression to determine whether there was an inflection point or knot in the relationship between BEUSII and each language outcome that could serve as a criterion level for hearing aid candidacy. This approach requires data from children with hearing loss who did not use amplification over a much wider range of hearing levels. Linear regression models for the relationships between BEUSII and each language outcome

were subjected to an iterative process where a segmentation point was identified by fitting the data with multiple piecewise regression models with knots from BEUSII values from 10 to 90 to find the point that produced the lowest Akaike information criterion and smallest mean square error (Muggeo, 2003). This method avoids the bias of preselecting segmentation points for piecewise regression using visual inspection of the data or other nonquantitative approaches. The intersection point between the linear regression model and 50th percentile for children with typical hearing was compared to the segmentation point for the piecewise regression method to develop a range of plausible unaided SII values for hearing aid candidacy based on risk of communication delays.

Results

Figures 2–4 compare the language outcomes for children with hearing loss to those for children with normal hearing for the three language outcome measures in the study. Linear regressions with hearing status as predictors of language outcomes were used to assess differences between children with typical hearing and children with hearing loss. PPVT-4 scores were higher, $F(1, 137) = 9.08$, $p = .0031$, for children with typical hearing ($M = 113.3$) than

Figure 2. Peabody Picture Vocabulary Test standard scores for children with normal hearing (green) and children with hearing loss (blue). Colored regions around the boxplots are symmetrical representations of the distribution of scores for each group. The box represents the interquartile range of the data for each group, and the vertical lines that extend from the box represent the range of the 95% confidence interval. The horizontal line in each boxplot represents the median for each group.

Figure 3. Comprehensive Assessment of Spoken Language (CASL) Syntax Construction standard scores for children with normal hearing (green) and children with hearing loss (blue). Colored regions around the boxplots are symmetrical representations of the distribution of scores for each group. The box represents the interquartile range of the data for each group, and the vertical lines that extend from the box represent the range of the 95% confidence interval. The horizontal line in each boxplot represents the median for each group.

Figure 4. Wechsler Abbreviated Scales of Intelligence (WASI) Vocabulary standard scores for children with normal hearing (green) and children with hearing loss (blue). Colored regions around the boxplots are symmetrical representations of the distribution of scores for each group. The box represents the interquartile range of the data for each group, and the vertical lines that extend from the box represent the range of the 95% confidence interval. The horizontal line in each boxplot represents the median for each group.

those for children with hearing loss ($M = 105.9$). CASL Syntax Construction scores were higher, $F(1, 199) = 4.18$, $p = .042$, for children with typical hearing ($M = 102.4$) than those for children with hearing loss ($M = 97.3$). WASI Vocabulary scores were not significantly different between groups, $F(1, 81) = 1.57$, $p = .21$, for children with typical hearing ($M = 54.5$) and children with hearing loss ($M = 51.4$). The 50th percentiles for children with normal hearing were 112 for the PPVT-4, 102 for the CASL, and 53 for the WASI Vocabulary subtest.

Linear regression models with BEUSII as predictors of each language outcome were estimated for the children with hearing loss. Figures 5–7 show the relationship between BEUSII and each language variable. The BEUSII was a significant predictor of PPVT-4 standard score ($R^2 = .25$, $p = .0014$), CASL syntax standard score ($R^2 = .11$, $p = .01$), and WASI Vocabulary t score ($R^2 = .17$, $p = .002$). The 50th percentile for each language outcome for children with typical hearing was used as one cutoff value for the BEUSII to indicate when children with hearing loss started to fall below children with typical hearing. The BEUSII intersection points equivalent to the 50th percentile for children with typical hearing are shown as the dashed vertical lines in Figures 5–7 and are 84 for the PPVT-4, 82 for the CASL, and 74 for the WASI Vocabulary subtest.

The second method of determining the point of BEUSII that put children at risk for delays in language was to use a piecewise regression approach to determine the point at which the relationship between BEUSII and language outcomes changes. This approach does not rely on comparisons to children with normal hearing but is based on identifying the

Figure 5. Peabody Picture Vocabulary Test standard scores as a function of better-ear unaided speech intelligibility index (SII) values. The blue line represents the linear relationship between the two variables. The red line represents the best fitting segments from the iterative piecewise regression model. The intersecting dashed lines represent the level of unaided SII associated with the median Peabody Picture Vocabulary Test score for children with normal hearing, and the intersecting solid lines represent the level of unaided SII associated with the knot for the best fitting iterative piecewise regression model.

Figure 6. Comprehensive Assessment of Language (CASL) Syntax Construction standard scores as a function of better-ear unaided speech intelligibility index (SII) values. The blue line represents the linear relationship between the two variables. The red line represents the best fitting segments from the iterative piecewise regression model. The dashed vertical line represents the level of unaided SII associated with the median Peabody Picture Vocabulary Test score for children with normal hearing, and the solid vertical line represents the level of unaided SII associated with the knot for the best fitting iterative piecewise regression model.

Figure 7. Wechsler Abbreviated Scales of Intelligence (WASI) Vocabulary standard scores as a function of better-ear unaided speech intelligibility index (SII) values. The blue line represents the linear relationship between the two variables. The red line represents the best fitting segments from the iterative piecewise regression model. The dashed vertical line represents the level of unaided SII associated with the median Peabody Picture Vocabulary Test score for children with normal hearing, and the solid vertical line represents the level of unaided SII associated with the knot for the best fitting iterative piecewise regression model.

Table 2. Final iterative piecewise regression models for each language outcome.

Language outcome	Knot	Akaike information criterion	MSE
PPVT-4	76	333.56	177.4
CASL Syntax Construction	72	345.6	156.8
WASI Vocabulary	80	322.8	152.6

Note. MSE = mean square error; PPVT-4 = Peabody Picture Vocabulary Test–Fourth Edition; CASL = Comprehensive Assessment of Spoken Language; WASI = Wechsler Abbreviated Scale of Intelligence.

point in the relationship between unaided hearing and language outcomes where the slope of the function changes significantly. Using iterative linear regression models, criterion levels were determined for each language outcome measure. Table 2 includes the Akaike information criterion and mean square error for the model with the lowest values. The BEUSII points based on piecewise regression are shown as solid vertical lines in Figures 5–7 and were 76 for the PPVT-4, 72 for the CASL Syntax Construction, and 80 for the WASI Vocabulary subtest.

Discussion

The goal of this study was to determine the level of unaided speech audibility that posed a risk to language outcomes among a group of children with hearing loss who either did not receive hearing aids or did not wear their hearing aids consistently. This information has the potential to improve the consistency of amplification provision for children with MBHL by providing evidence for the level of unaided hearing that was associated with delays in language development. The relationship between unaided speech audibility (SII) and receptive vocabulary (PPVT-4), expressive vocabulary (WASI), and syntax (CASL Syntax Construction) was examined using linear models. Two approaches were compared to generate estimates of the level of unaided hearing associated with poorer language outcomes: using the median for a group of children with typical hearing matched for age and SES and using an iterative, piecewise regression approach that derived criterion levels of audibility based on the linear relationship between unaided hearing and language outcomes statistically. Current hearing aid candidacy criteria based on audiometric thresholds have not been validated using samples of children with hearing loss and do not take into account the influence of ear canal acoustics on a child's audiometric thresholds. Developing clinical recommendations for a hearing aid fitting criterion for children with MBHL based on the relationship between unaided SII and language outcomes was a secondary goal.

The first potential criterion for hearing aid candidacy was to examine the level of unaided audibility that was associated with the median language levels for children with typical hearing across measures of receptive and expressive vocabulary and syntax. For the hearing aid candidacy criterion based on the median language scores of children with typical hearing, the range of BEUSII values was 74–84

across measures. Although there was individual variability in language outcomes across levels of unaided audibility, there was convergence across the three language measures on values around BEUSII = 80. Depending on the age and ear canal acoustics of a given child, these unaided SII values would translate to a range of BEPTAs between 20 and 30 dB HL for the participants in this study. In combination, the results suggest that children with BEUSII values lower than this range may be at risk for language scores that lag behind age- and SES-matched peers with typical hearing.

The second criterion used an iterative piecewise regression model to find the point in the relationship between unaided audibility and language outcomes that minimized the residual error of the model. The levels of BEUSII associated with breakpoints in the linear relationship between unaided SII and language outcomes yielded criteria of BEUSII from 72 to 80 across outcome measures. The advantage of this approach is that the criterion levels of audibility are based on a statistical method that is blind to the hypothesis of the study. The levels of unaided hearing that were derived from the piecewise regression approach were in good agreement with the criterion based on median performance for children with typical hearing. Children with hearing loss from the larger OCHL cohort who had well-fitted hearing aids and consistent hearing aid use achieved comparable language scores to the levels derived from the piecewise regression models (Tomblin et al., 2015). Collectively, these results suggest fitting hearing aids for children who have a BEUSII value of 80 or lower would be warranted to minimize the likelihood of communication differences from peers with typical hearing. Adopting such a criterion could minimize the potential risks of language delay in children with MBHL. Using the unaided SII as a candidacy criterion for hearing aids also would reflect the individual variability related to ear canal acoustics on hearing thresholds measured with insert earphones or earmolds, which is not easily accomplished with the dB HL audiogram. If an unaided SII criterion of 80 had been used by the audiologists who fitted children in this study, seven of the 11 children (with dB HL BEPTA varying from 17 to 30 dB) who were not fitted with amplification in the current study would have been considered candidates for amplification based on BEUSII values less than 80.

Although this study is a preliminary attempt to validate a hearing aid candidacy criterion for children with MBHL based on the unaided SII, there are a number of

limitations that should be mentioned. Even if children with MBHL are fitted with amplification, data suggest that consistent hearing aid use is likely to remain a barrier to improved auditory access and outcomes (Walker et al., 2013). However, using a consistent hearing aid candidacy criterion based on the unaided SII would standardize recommendations for amplification to a greater extent than is possible based on dB HL audiometric thresholds. More consistent recommendations may provide families with greater confidence in the potential benefits that could be achieved with hearing aids and may facilitate more consistent use than current clinical situations where audiologists may appear uncertain about the benefits of amplification for children with MBHL. Using unaided audibility as a criterion for hearing aid fitting also provides an intuitive comparison for aided audibility if a hearing aid is fitted, allowing the audiologist to directly quantify the improvement in audibility that is achieved with the device. Additionally, the current study was also based on a sample of children with hearing loss without additional developmental comorbidities, from homes where spoken English is the primary language and from more economically advantaged homes than the general population. Although this allowed for a slightly more homogeneous sample in these areas, the outcomes reported here may be different than those that would be observed in a more representative sample of the population of children with hearing loss.

Clinical Implications

Audiologists who perform diagnostic assessment or make decisions about hearing aid candidacy for infants and children who have hearing loss can use the data from this study as evidence to support hearing aid candidacy criteria based on unaided SII. The convergence of data between criteria based on achieving levels of language development similar to peers with typical hearing and a statistical model suggests that children with unaided SII of 80 or less should be considered candidates for amplification. Hearing aid candidacy is a complex decision process that includes many factors beyond the child's level of hearing, including the parents' or caregivers' goals related to hearing aids and communication mode, the child's other medical or developmental needs, and many others. Each of the models associating unaided audibility and language outcomes only accounted for a small amount of the variability in language outcomes for the children with hearing loss in the study.

Nonetheless, using unaided speech audibility as the criterion for hearing aid candidacy for children provides an alternative to the dB HL audiogram that takes into account individual differences in ear canal acoustics and audibility for speech. Recent research has suggested that a wide range of factors affects language development in children who have mild-to-severe hearing loss, including aided speech audibility and hearing aid use (e.g., Tomblin et al., 2015). However, at the time of hearing aid candidacy decisions, the only information available to the audiologist is the child's hearing levels and ear canal acoustics. The analyses

presented in this study should not be taken as support for the idea that unaided speech audibility is a potent predictor of later language outcomes, primarily because this subgroup of children in this analysis did not receive or did not use hearing aids and have outcomes that would not likely be reflective of children who used hearing aids. However, the current clinical approach of counseling parents or caregivers using thresholds from the behavioral audiogram can be challenging because the categories of degrees of hearing loss are often not meaningful predictors of the challenges that children with hearing loss might face. Describing audibility loss instead of hearing loss provides a meaningful context for the impact of the child's hearing levels on communication and a direct comparison to the child's aided hearing levels, if hearing aids are fitted.

There are also challenges to the implementation of a hearing aid fitting criterion based on unaided audibility. Audiologists are currently trained to use the dB HL audiogram as the standard method of quantifying hearing. Changing to a hearing aid criterion based on unaided audibility from estimates of hearing in dB SPL may be a challenging shift from current practice, and education and support will be needed to facilitate that transition. Audiologists currently incorporate the individual ear canal acoustics of children into the process of fitting hearing aids by measuring the child's RECD as part of the hearing aid verification process, but the practice of measuring RECD at the time of diagnostic assessment to estimate unaided audibility is not the current clinical practice. In-ear calibration of the stimulus level for audiometric and auditory brainstem response assessment, as is currently used for the measurement of otoacoustic emissions, would mitigate the need to account for the effects of ear canal acoustics on thresholds, as the level could be simultaneously specified in dB HL and dB SPL in the ear canal. Until equipment that includes that capability is widely available in clinics, audiologists who are unable to measure the child's RECD at the time of the hearing assessment can use an age-related average RECD to generate an estimate of unaided audibility without an individual measure. This method would not be as accurate for children who have ear canals that are smaller or larger than peers of the same age, tympanostomy tubes, perforations, or anatomical differences in their ear canal. Further research to address these barriers to clinical implementation will help to support the adoption of a hearing aid fitting criterion based on unaided audibility.

Conclusions

The goal of this study was to examine the levels of unaided hearing that were associated with risks for language delay in a group of children with mild-to-severe hearing loss. A secondary goal was to use these data to develop recommendations for a clinical criterion for hearing aid fitting based on unaided audibility rather than the behavioral audiogram. Criteria were developed based on (a) the level of unaided audibility that was equivalent to the median level of outcome performance for a matched group of children

with typical hearing and (b) the usage of a statistical model to determine the level of unaided hearing where language outcomes started to deviate from the median levels of age- and SES-matched peers with typical hearing. Both criteria converged on a level of unaided SII around 80. Collectively, these results suggest that children with hearing loss who have unaided audibility of 80 or less should be considered candidates for amplification.

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