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Perceptual Implications of Level- and Frequency-Specific Deviations from Hearing Aid Prescription in Children

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Ryan W. McCreery*
Marc Brennan*
Elizabeth A. Walker†
Meredith Spratford*

Abstract

Background: The purpose of providing amplification for children with hearing loss is to make speech audible across a range of frequencies and intensities. Children with hearing aids (HAs) that closely approximate prescriptive targets have better audibility than peers with HA output below prescriptive targets. Poor aided audibility puts children with hearing loss at risk for delays in communication, social, and academic development.

Purpose: The goals of this study were to determine how well HAs match prescriptive targets across ranges of frequency and intensity of speech and to determine how level- and frequency-dependent deviations from prescriptive target affect speech recognition in quiet and in background noise.

Study Sample: One-hundred sixty-six children with permanent mild to severe hearing loss who were between 6 months and 8 years of age and who wore HAs participated in the study.

Data Collection and Analysis: Hearing aid verification and speech recognition data were collected as part of a longitudinal study of communication development in children with HAs. Hearing aid output at levels of soft and average speech and maximum power output were compared with each child's prescriptive targets. The deviations from prescriptive target were quantified based on the root-mean-square (RMS) error and absolute deviation from target for octave frequencies. Children were classified into groups based on the number of level-dependent deviations from prescriptive target. Frequency-specific deviations from prescriptive target and sensation levels (SLs) were used to estimate the proximity of fittings across the frequency range. Lexical Neighborhood Test (LNT) word recognition in quiet and Computer-Assisted Speech Perception Assessment (CASPA) phoneme recognition in noise were compared across level-dependent error groups and as a function of SL at 4 kHz.

Results: Children who had deviations from prescriptive target at all three input levels had poorer LNT word recognition in quiet than children who had fittings that matched prescriptive target within 5 dB RMS at all three input levels. Children with lower 4 kHz SLs through their HAs had poorer LNT recognition in quiet and CASPA phoneme recognition in noise than children with higher aided SLs.

Conclusions: Children with HAs fitted to provide audibility for speech across a range of inputs and frequencies had better speech recognition outcomes than peers with HAs that were not optimally fitted to prescriptive targets.

Key Words: amplification, children, hearing aids, hearing aid prescription, hearing loss, pediatric audiology, speech perception

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*Audibility, Perception, and Cognition Laboratory, Boys Town National Research Hospital, Omaha, NE; †Departments of Communication Sciences and Disorders, University of Iowa, Iowa City, IA

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Corresponding author: Ryan W. McCreery, Audibility, Perception, and Cognition Laboratory, Boys Town National Research Hospital, 555 North 30th Street, Omaha, NE 68131; Email: Ryan.McCreery@boystown.org

Abbreviations: CASPA = Computer-Assisted Speech Perception Assessment; DSL m i/o = Desired Sensation Level multistage input/output; HA = hearing aid; LNT = Lexical Neighborhood Test; MPO = maximum power output; NAL-NL2 = National Acoustics Laboratories Nonlinear Formula, Version 2; OCHL = Outcomes of Children with Hearing Loss study; RECD = real-ear-to-coupler difference; RMS = root-mean-square; SII = speech Intelligibility Index; SL = sensation level; SNR = signal-to-noise ratio

INTRODUCTION

Hearing aids provide auditory access for children with mild to severe hearing loss when fitted in a manner that optimizes audibility for speech. Children who have higher aided audibility through their hearing aids (HAs) have stronger general language abilities (Tomblin et al, 2014; Tomblin, Walker, et al, 2015), better parent ratings on auditory development questionnaires, and higher speech-recognition scores in quiet and in noise (McCreery et al, 2015a) than peers with poorer aided audibility. However, children's HAs may not be fitted in a manner that promotes aided audibility across the range of input levels and frequencies that are necessary for speech understanding. Several recent studies indicate that up to one-third of children who wear HAs may not have adequate aided audibility for average input levels of speech based on their degree of hearing loss, and more than half may have significant deviations from prescriptive targets (Strauss and van Dijk, 2008; McCreery et al, 2013; McCreery et al, 2015b). Most previous studies of HA fitting accuracy in children have focused on the overall accuracy at an input level equivalent to average speech (60 or 65 dB SPL), averaged across frequencies. This broad approach has helped to identify that a subset of children who wear HAs have poorer audibility than what would be prescribed based on their degree of hearing loss. However, an analysis that describes deviations from prescriptive target across a broader range of input levels and frequencies may help to identify more specifically the effects of underamplification in children. The goals of this study were to examine level- and frequency-specific deviations from prescriptive targets in a large cohort of children who wear HAs and to determine if specific patterns of fitting errors affected aided speech recognition.

Hearing Aid Prescription for Children

Hearing aid prescriptions determine the amount of amplification that is recommended for a given listener based on their frequency-specific audiometric thresholds. Prescriptive approaches are a systematic approach to providing audibility for speech while also preventing discomfort or overamplification at higher input levels (Ching et al, 2013b). Two prescriptive methods have been widely validated for children who wear HAs: the National Acoustics Laboratories Nonlinear Formula, Version 2 (NAL-NL2; Keidser et al, 2011) and the Desired Sensation Level multistage input/output, Version 5 (DSL m i/o; Scollie et al, 2005). Both formulae have been validated for use with children, including a randomized controlled trial where equivocal results were observed among children fitted with each formula (Ching et al, 2013a). Hearing aid fittings that more closely approximate prescriptive targets have been shown to provide more consistent speech audibility across a range of degrees of hearing loss than fittings with significant deviations (McCreery et al, 2013).

With the widespread use of multichannel amplitude compression in HAs, the amount of amplification can be adjusted for different input levels across the dynamic range for speech. With amplitude compression, the gradual reduction in the amount of amplification as the input level increases helps to balance audibility and comfort across a wide range of listening environments with varying sound levels (Jenstad et al, 2000). Before the development of multichannel amplitude compression, linear amplification strategies made it difficult to achieve audibility for low-level speech information without sacrificing listening comfort at high-level inputs. Both NAL-NL2 and DSL m i/o provide prescriptive targets across a range of input levels for speech, as well as prescribed limits for the swept pure-tone signal that is used to measure the maximum power output (MPO) of the HA. Verifying that the HA gain and output closely approximate prescriptive targets at multiple input levels is recommended in pediatric amplification clinical practice guidelines to ensure audibility and comfort are achieved in everyday listening environments (American Academy of Audiology, 2013).

The extent to which prescriptive targets are approximated at multiple input levels and across the frequency range for speech has been documented in a few studies. Most studies that have investigated the proximity of HA fittings to prescriptive targets have examined an average speech-input level (Strauss and van Dijk, 2008; McCreery et al, 2013; 2015a). The proximity of the fitting to target can be expressed as either an absolute difference between the output of the HA and the prescriptive target or an average of deviations from specific frequencies. Strauss and van Dijk (2008) examined how closely HA fitting approximated average speech and MPO using absolute deviation from targets in a group of twenty 3- to 6-year-old children. They found that many children had substantial deviations from prescriptive target for both average speech and MPO.

The proximity of the fittings for soft speech was not reported in that study. McCreery et al (2013) also reported root-mean-square (RMS) average deviations from prescriptive targets at 500, 1000, 2000, and 4000 Hz. The study examined soft and average speech input levels for 195 children who wore HAs, but did not report data for MPO. Based on a criterion of ≥5 dB RMS error, more than half of the children in the study had significant deviations from prescriptive target for average speech. More positive results were reported in a recent cross-sectional study conducted in Canada (Moodie et al. in press). Unlike some of the previous studies, approximately 80% of the children who wore HAs were within 5 dB RMS error of prescriptive targets across frequencies for soft, average, and loud speech. In addition, 72% were within 5 dB RMS error of prescriptive targets for MPO. These studies highlight the considerable variation in fitting outcomes that are observed among different groups of children who wear HAs. The impact that deviations from target may have on aided audibility and speech recognition have not been elaborated.

The Importance of Level- and Frequency-Specific Audibility

The effects of level- or frequency-specific deviations from prescriptive targets and the effects that such deviations might have on speech recognition have not been widely reported. Children may have deviations from prescriptive target that cause audibility deficits only for specific input levels or specific frequency ranges, particularly frequencies above 4 kHz (Kimlinger et al, 2015). These high-frequency deviations could negatively impact their auditory access and language abilities (Koehlinger et al, 2015), but may not be apparent from measures of average speech audibility or when fitting errors are averaged into a single RMS error value across frequencies. An examination of the specific level- and frequency-dependent patterns of fitting errors might help to identify challenges in HA verification practices for children and better optimize audibility and comfort across different listening situations. The perceptual consequences of level- and frequency-dependent fitting errors may have varying effects depending on how audibility is affected or if unnecessary distortion is introduced. There are several different mechanisms by which failure to match prescriptive targets across different input levels and frequencies could negatively impact perception for children.

The MPO of the HA is the response of the HA to a high-level (generally 85 or 90 dB SPL) pure-tone sweep and is thought to represent the upper limit of amplification. The rationale for measuring the MPO as part of the verification process is to ensure that the HA does not exceed predicted loudness discomfort levels at high input levels and to prevent amplification-induced hearing loss (Ching et al, 2013b). The risks of permanent threshold changes due to amplification among children with mild to severe hearing losses appear to be small (McCreery et al, 2016). The perceptual effects of setting the MPO below prescribed levels have not been directly studied in children, but evidence from adults with hearing loss suggests that setting the MPO below prescribed levels may limit aided speech recognition in noise and reduce sound quality (Kuk et al, 2011). An MPO that is below prescribed levels may reduce audibility or increase the amount of compression that is applied to speech at lower input levels, causing reduced speech recognition. There is evidence that MPO may be consistently below prescribed levels for many children. Strauss and van Dijk (2008) found that many preschoolers who wore HAs had MPO settings that were below prescribed levels, even in some cases when average speech matched prescriptive targets.

Similarly, failure to verify the match to prescriptive targets for input levels equivalent to soft (50 or 55 dB SPL) or loud (75 or 80 dB SPL) speech may also lead to inadequate or excessive amounts of amplitude compression. Inadequate amplitude compression may limit the audibility of input levels equivalent to soft speech, whereas excessive amplitude compression may lead to unnecessary distortion of the speech input. Research with adults has suggested that both inadequate and excessive amplitude compression can negatively impact speech-recognition abilities for listeners who wear HAs (Brennan and Souza, 2009; Jenstad and Souza, 2007). While studies with children suggest that appropriately prescribed amplitude compression can improve speech recognition compared with linear amplification (Jenstad et al, 1999; or see McCreery et al, 2012 for review), inadequate or excessive amplitude compression might result in differences in audibility for speech that are only apparent when assessing multiple input levels. Differences in audibility across input levels could negatively affect perception in children with hearing loss.

The perceptual and developmental effects of limited high-frequency bandwidth have been more widely studied than the effects of level-dependent deviations in prescriptive target. Moodie et al (in press) reported that the most significant deviations from prescriptive target in their sample of relatively well-fit children with HAs were at 4 kHz. Reductions in speech recognition (Stelmachowicz et al, 2004), phoneme acquisition (Moeller et al, 2007), word learning (Pittman, 2008), and morphosyntactic development (Koehlinger et al, 2015) for children who wear HAs have all been linked to reduced high-frequency bandwidth through HAs. In particular, a study by Koehlinger et al (2015) found that the sensation level (SL) of speech at 4 kHz predicted individual differences in morphosyntactic development in children who wore HAs, whereas a broader measure of speech audibility across frequencies, the aided Speech Intelligibility Index (SII), did not. Some limitations of the audible bandwidth may be related to the bandwidth of the HA receiver or the child's degree of hearing loss (Kimlinger et al, 2015). High-frequency bandwidth also may be limited by deviations from prescriptive target in the high frequencies, but the relative contributions of these factors to audibility has not been described in a large group of children who wear HAs. High-frequency deviations from prescriptive target may not be reflected in aggregate measures of deviation from target across the range of average speech, such as the RMS error, which is based on the geometric mean of the deviations at 500, 1000, 2000, and 4000 Hz. Although limited high-frequency bandwidth is known to negatively impact speech recognition in children with hearing loss in laboratory studies where the bandwidth is restricted through filtering (Stelmachowicz et al, 2001), the magnitude of this effect in children who wear HAs with a range of high-frequency audibility has not been reported.

Rationale and Hypotheses for the Current Study

Aided audibility has been shown to affect outcomes in children who wear HAs, but the effect that level- and frequency-dependent variabilities in aided audibility have on children's aided speech recognition has not been widely examined. Hearing aid verification and speech recognition data from a large cohort of children who participated in the Outcomes of Children with Hearing Loss study (OCHL; Moeller and Tomblin, 2015) were analyzed to address two research questions:

(1) How prevalent are level- and frequency-dependent deviations from prescriptive targets in children who wear HAs? Based on previous research on deviations from prescriptive target for average speech, more than 50% of children who wear HAs were predicted to have deviations more than 5 dB RMS error from prescriptive target that occurred for either soft-input levels or MPO. The SL of speech at 4 kHz was expected to decrease in some children because of a combination of increasing degree of hearing loss and greater deviations from prescriptive target.

(2) How do level- and frequency-dependent deviations from prescriptive targets impact speech recognition in quiet and in noise? Children with level-dependent deviations from prescriptive target were expected to have poorer speech recognition in quiet and in noise than children with fittings that better approximated prescriptive targets. Children with greater deviations from prescriptive target at 4 kHz were expected to have lower SLs for speech at 4 kHz and poorer speech recognition in quiet and in noise than children with smaller deviations and higher SLs for speech.

These questions were selected to provide evidence to support the notion that clinical verification of level- and frequency-dependent audibility is an important practice for children who wear HAs.

METHOD

Participants

Two hundred and ninety-two children with mild-to-severe permanent hearing loss between the ages of 6 months and 8 years who wore air-conduction HAs were considered for inclusion. The cohort was recruited as part of a large, multicenter study of developmental outcomes in children who use HAs, known as the OCHL study. A battery of developmentally appropriate speech, language, and hearing assessments was given annually to each child older than the age of two and twice a year for children under the age of two over the time course of four years (Tomblin, Harrison, et al, 2015). To be included in the current analyses, children needed to have at least one visit during the OCHL study where ear- and frequency-specific audiometric threshold and measured HA verification data were obtained. Children with frequency lowering signal processing in their HAs were excluded from this analysis because of challenges in estimating frequency-specific deviations when the output of the HA is shifted in the frequency domain. A subset of children in the study who could not participate in in situ verification or provide a measured real-ear-to-coupler difference (RECD) received verification based on age-related average RECD values, but data from those visits were excluded. One hundred and sixty-six children met the inclusion criteria for the first aim of the study, which examined level- and frequency-dependent deviations from prescriptive targets. A subset of 145 children between 4 and 8 years of age who had audiometric, HA verification, and open-set speech-recognition data from the same visit were included in analyses related to the effects of level- and frequency-dependent deviations in HA fitting on aided speech recognition under the second aim of the study. For children with multiple measurements of speech recognition of the same stimulus type across different study visits, only the speech recognition data from the first visit were analyzed to minimize violations of assumptions of independence from correlated measures over time within the same participant. The number of participants at each study visit is shown in the first column of Table 1.

Assessment of Audiometric Thresholds

Audiologists assessed audiometric thresholds at each study visit in a sound-treated audiometric test booth or

Table 1. Total Number of Children for Each Visit, Ear, and Input Level

Level	50 dB SPL		65 dB SPL		MPO (85 dB SPL)	
	Right	Left	Right	Left	Right	Left
Visit 1 (n = 144)	144	140	141	140	51	49
Visit 2 (n = 156)	156	151	152	150	88	85
Visit 3 (n = 166)	165	157	166	159	140	132
Visit 4 (n = 117)	113	107	114	109	113	107

mobile test suite. Audiometric thresholds for air- and bone-conduction were measured for as many octave frequencies (250–8000 Hz) as possible during the test session using insert earphones with foam tips unless contraindicated. Interoctave frequencies were tested for cooperative participants if a difference of ≥15 dB was observed between octave test frequencies. Developmentally appropriate behavioral methods of audiometric assessment were used depending on the child's age and developmental abilities, including visual reinforcement audiometry, conditioned play audiometry, or conventional audiometry. Only audiometric results judged by the audiologist of fair or good reliability were included in the analyses that follow.

Hearing Aid Verification

Probe microphone measures were completed at each visit to estimate the output of the HA in the child's ear for verification purposes. The speech stimulus for verification was the carrot passage from the Audioscan Verifit (Dorchester, ON, Canada). In situ probe-microphone measurements with the HA in the child's ear were completed when the child's cooperation permitted. Individually measured RECD values with the child's personal earmolds or insert foam tips were applied to measurements of HA output in the 2-cm^3 coupler of the Audioscan Verifit to simulate the output of the HA in the child's ear canal. The clinical audiologists who fitted the children in the study with their HAs reported using the DSL prescriptive method for all but two of the children in the study (McCreery et al, 2013). The two children fitted using a different prescriptive reference were excluded. The frequency-specific deviations from prescriptive targets at 250, 500, 1000, 2000, 4000, and 6000 Hz for soft (50 dB SPL) and average (65 dB SPL) speech and the MPO were estimated in dB whenever data at these frequencies were available (i.e., in cases where an audiometric threshold was not available at a specific frequency). The RMS error for each fitting was calculated for each child using the geometric mean of the deviations from prescriptive targets for each input level (soft and average speech and MPO) at 500, 1000, 2000, and 4000 Hz for purposes of comparison with frequency-specific deviations. Table 1 summarizes the number of data points that were available for each input level across each study visit.

Aided Audibility for Speech

The SII (ANSI, 1997) was used to calculate aided audibility. The aided audibility of the long-term average speech spectrum was calculated for each listener, ear, and input level using the 1/3-octave-band calculation method. The standard band-importance weighting function from the ANSI SII standard was applied. The free field to eardrum transform from the SII was used to convert levels of speech to free field. The levels of speech and threshold-equivalent noise in each frequency band were entered into a spreadsheet to calculate SL for each 1/3-octave band. The SL in each frequency band was divided by 30 dB. The SII for each condition was generated by multiplying the SL by the importance weight for each band and summing the products for all bands.

Aided Speech Recognition in Quiet and in Noise

The Lexical Neighborhood Test

The Lexical Neighborhood Test (LNT) was completed with the children wearing their HAs as part of the 4- and 5-year-old study visits (Kirk et al, 1995). One-hundred twenty-one children had LNT and HA verification data for the same visit. The average age of the children who provided LNT data for this analysis was 5.1 years. The LNT is an open-set monosyllabic-word recognition task. The LNT stimuli are organized into Easy and Hard lists based on lexical frequency and neighborhood density. Easy lists contain words with high lexical frequency and low lexical neighborhood density, whereas Hard lists contain words with low lexical frequency and high lexical neighborhood density. For the current study, the LNT-Hard was used to represent performance, as previous analyses did not show differences in performance between LNT-Easy and LNT-Hard for this cohort (McCreery et al, 2015b). The LNT was presented in quiet using recorded stimuli at a presentation level of 65 dBA from a speaker at 0° azimuth.

The Computer-Assisted Speech Perception Assessment

The Computer-Assisted Speech Perception Assessment (CASPA) was administered to the children with and without their HAs on, as part of the seven-, eight-, and nine-year-old visits (Boothroyd, 1999). Eighty-three children had CASPA and HA verification data for the same visit. The average age of the children who provided CASPA data for this analysis was 8.3 years. CASPA is a measure of monosyllabic word recognition and consists of 30 stimulus lists that each includes 10 monosyllabic words. Each list is balanced for phonemic content and can be scored based on the percentage of words or phonemes correct. Recordings of CASPA stimuli were presented via loudspeaker at 0-degree azimuth with the steady-state speech spectrum noise level at 55 dBA and the level of the talker at 50, 65, and 75 dBA. Steady-state, speech-spectrum noise was presented at a constant 55 dBA, resulting in three signal-to-noise ratios (SNRs) (−5, +10, and +20 dB). The scores used in this analysis were the percent correct of 30 phonemes for the aided conditions only.

Statistical Analyses

The R software interface (Version 3.1.1; R Core Team, 2014) with the lme4 (Bates et al, 2014) and ggplot2 (Wickham and Chang, 2014) packages were used to generate statistical models and plots of the data, respectively. Linear mixed models were used to assess relationships between variables of interest while acknowledging correlations between observations obtained from the same participants over time or between ears. In each linear mixed model, a random intercept was included for each participant. In some models, a second level factor for ear was included when left and right ears of the same participant were analyzed in the same model. All possible interactions of predictor variables were included in each model, but higher-order interactions that were not significant are not reported to simplify the discussion of the results. Type I error rate was controlled using the False Discovery Rate (Benjamini and Hochberg, 1995). Inspection of the distribution of residuals for each statistical model was completed to determine if assumptions of normality were met.

The effects of deviations from prescriptive target on speech recognition were evaluated by placing children into categories based on the number of input levels where the RMS error was >5 dB. The proximity of the fitting to prescriptive targets at soft (50 dB SPL), average (65 dB SPL), and MPO (90 dB SPL) input levels was used to create categories where children had deviations >5 dB at none, one, two, or all three input levels. In addition, the proximity of the HA fitting to prescriptive target at 4 kHz and the SL (HA output minus threshold) at 4 kHz were estimated to characterize the proximity of HA fittings to targets in the high frequencies and the effects of audible bandwidth on aided speech recognition. Speech recognition was compared across each category of error for level-dependent error groups and across SL at 4 kHz to determine the influence of level- and frequency-dependent deviations from prescriptive target on perception.

RESULTS

Proximity of Fitting to Prescriptive Target by Input Level in RMS Error

Figure 1 shows the RMS error across level for each ear. A linear mixed model with a random intercept for each participant was used to evaluate differences in RMS error across the verification input level, visit, and ear. The mean RMS error for average speech across all participants was 7.7 dB. There was no significant difference in the RMS error between right and left ears ($F_{[1,\ 2929]} = 3.01$, $p = 0.09$). The main effects for level ($F_{[2,\ 2943]} = 6.67$, $p < 0.001$) and visit ($F_{[3,\ 3178]} = 9.79$, $p < 0.001$) were significant. Post hoc comparisons for level indicated that the RMS error between 50 and 65 dB inputs was not significantly different ($p = 0.04$; mean difference = 0.31 dB), but the RMS error was significantly lower at 90 dB than at 65 dB ($p = 0.01$; mean difference = 0.5 dB) and 50 dB ($p < 0.001$; mean difference 0.81 dB). Post hoc comparisons for visit indicated that RMS error decreased significantly at each study visit. Significant improvements were noted across Visit 1–Visit 2 ($p < 0.0001$; mean difference = 0.92 dB), Visit 2–Visit 3 ($p < 0.0001$; mean difference = 1.3 dB), and Visit 3–Visit 4 ($p < 0.0001$, mean difference = 1.5 dB). Table 2 shows the percentage of children at each visit who exceeded the 5 dB RMS error criterion for each ear and verification input level. For 50-dB and 65-dB SPL input levels, one-half to two-thirds of the sample had RMS errors >5 dB in at least one ear for each visit.

To determine the impact of RMS error on audibility for speech across different input levels, a linear mixed model with a random intercept for each participant was conducted with the RMS error, input level, and visit as predictors of the aided SII. The effect of RMS error on aided SII was significant ($F_{[1,\ 3188]} = 549.7$, $p < 0.001$) with increasing RMS error associated with poorer aided audibility, as expected. Aided audibility did not differ across study visits or between ears. As would be expected, the aided SII increased from soft to average speech input levels. There was no significant interaction between RMS error and level ($F_{[2,\ 3188]} = 3.29$, $p = 0.52$), suggesting that the negative effect of RMS error on aided audibility was similarly negative across input levels.

To analyze the different combinations of deviations from prescriptive target across levels, children were categorized based on the RMS error from prescriptive target for soft and average speech and MPO. Because there was no significant effect of ear in the mixed model examining RMS error by input level and visit, the categorization of RMS error across level was based on the better-fitted ear, which was defined as the ear with the smallest RMS error for average speech. Table 3 shows the number of children in each group based on the RMS

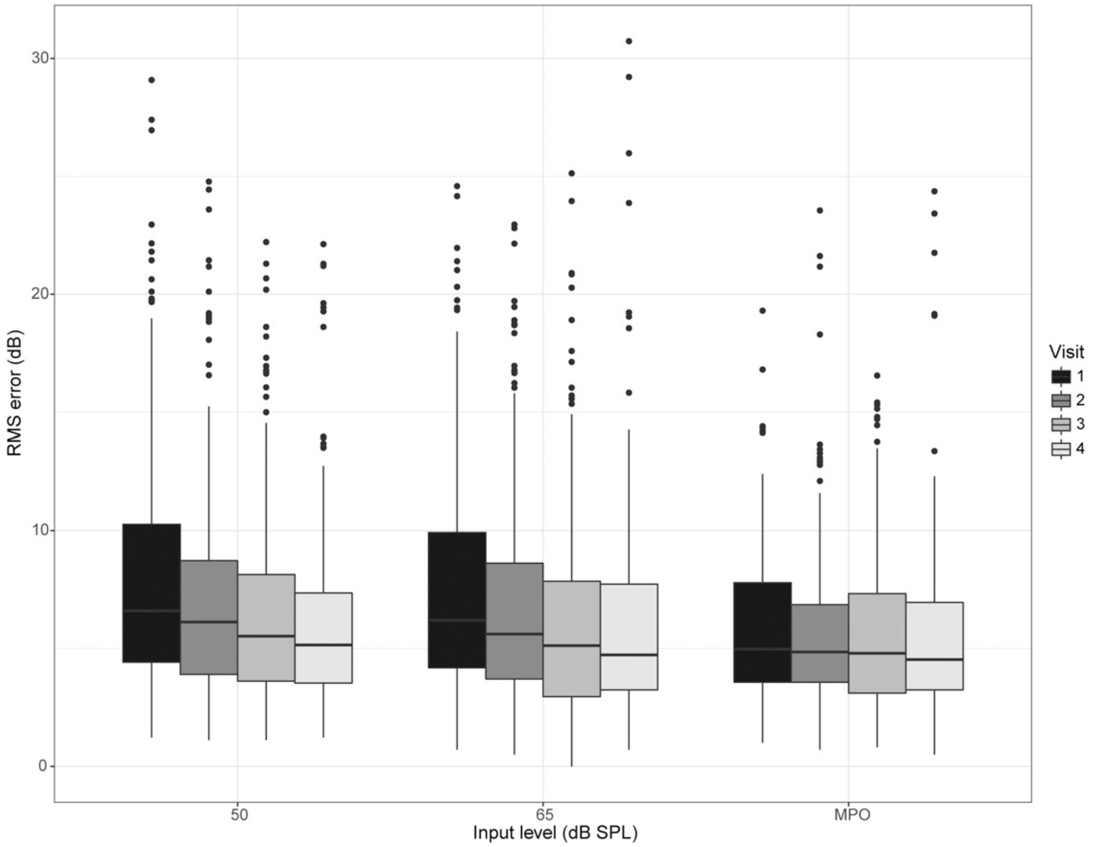

Figure 1. The RMS error for soft speech (50 dB SPL), average speech (65 dB SPL), and MPO (85 dB SPL) as a function of visit. The boxes represent the interquartile range (25th–75th percentiles), the horizontal line across each bar represents the median and the whiskers represent the range of the 5th to 95th percentiles. Black circles represent individual data points that fall outside of the range of the 5th to 95th percentiles.

errors at each input level. Across visits, 34% of children had HA fittings that were within 5 dB RMS error of prescriptive targets at all levels, and 21% of children had HA fittings where the RMS error was >5 dB for soft and average speech and MPO. Smaller subsets of the sample had RMS errors >5 dB at a single input level or a combination of two input levels.

Absolute Deviations from Prescriptive Target by Frequency and Input Level

Figure 2 shows the frequency-specific deviations from the prescriptive target by level for each ear. The frequency-specific deviation from the prescriptive target (HA output—prescriptive target at each frequency) and frequency-specific SL (HA output—audiometric threshold converted to dB SPL using the conversion from the ANSI SII standard) were calculated. The frequency-specific deviation from the prescriptive target was used as a metric of fitting quality across frequency. Because the prescribed SL varies depending on the child's degree of hearing loss, the SL was used to estimate the frequency-specific audibility of speech. A linear mixed model with ear, level, and frequency as factors was used to evaluate differences in the deviation from prescriptive target as a function of these factors. As with the level-specific model, the overall difference between ears was not significant ($p = 0.09$). The level by frequency interaction was significant ($F_{[10,\ 14,225]} = 28.03$, $p < 0.001$). The results from post hoc comparisons across level and frequency are shown in Table 4. The level by frequency interaction revealed that deviations from prescriptive target decreased as the input level increased for each frequency, except at 6 kHz where the deviation from target increased between average speech and MPO. In addition, deviations from prescriptive target increased as frequency increased.

Table 2. Number and Percentage of Children with RMS Error >5 dB by Level, Ear, and Visit

Level	50 dB SPL		65 dB SPL		MPO (85 dB SPL)	
	Right	Left	Right	Left	Right	Left
Visit 1	99/69%	95/68%	92/65%	92/66%	26/51%	24/48%
Visit 2	90/58%	91/60%	81/53%	87/58%	35/40%	44/52%
Visit 3	81/49%	93/59%	78/47%	84/53%	63/45%	66/50%
Visit 4	60/53%	55/51%	57/50%	45/41%	52/46%	48/45%

Table 3. Classification of Fitting Errors by Input Level in the Better-Fitted Ear for Each Visit

	Visit 1	Visit 2	Visit 3	Visit 4	Total
All levels <5 dB RMSE	33 (22%)	47 (30%)	52 (31%)	35 (30%)	167 (34%)
Only Soft >5 dB RMSE	12 (8.1%)	10 (6.3%)	22 (13.1)	16 (14%)	60 (12%)
Only Average >5 dB RMSE	11 (7.4%)	13 (8.2%)	9 (5.4%)	3 (2.6%)	36 (7%)
Only MPO > 5 dB RMSE	8 (5.4%)	8 (5.4%)	15 (9%)	17 (15%)	48 (10%)
Soft and average >5 dB RMSE	58 (38.9%)	48 (30%)	25 (14.9%)	17 (15%)	46 (9%)
All levels >5 dB RMSE	25 (16.8%)	23 (14.6%)	34 (20.2%)	22 (19%)	104 (21%)
Other	2 (1.4%)	9 (5.7%)	11 (6.6%)	5 (4.4%)	27 (6%)

Notes: Better-fitted ear is defined as the ear with the smallest RMS error for average speech. Other category included ears with less frequently occurring error patterns >5 dB RMS error for soft and MPO or >5 dB RMS error for both average and MPO. RMSE = RMS error.

Figure 3 shows the frequency-specific SLs for average speech for each child's better-fitted ear. The SL prescribed for DSL decreases as the audiometric threshold increases, leading to variance in SL across participants that is related to their degree of hearing loss. To estimate the amount of variance in SL that was related to frequency-specific deviations from prescriptive target while accounting for differences in degree of hearing loss, linear regression models were conducted with audiometric threshold and deviation from prescriptive target as predictors of SL for average speech at 500, 1000, 2000, and 4000 Hz. Models were completed using the better-fitted ear for each child consistent with the previous analysis. Table 5 shows the model results for each linear regression. For each frequency, audiometric threshold and fitting error were significant predictors of SL. Lower audiometric thresholds and lower fitting errors led to higher SLs for average speech across

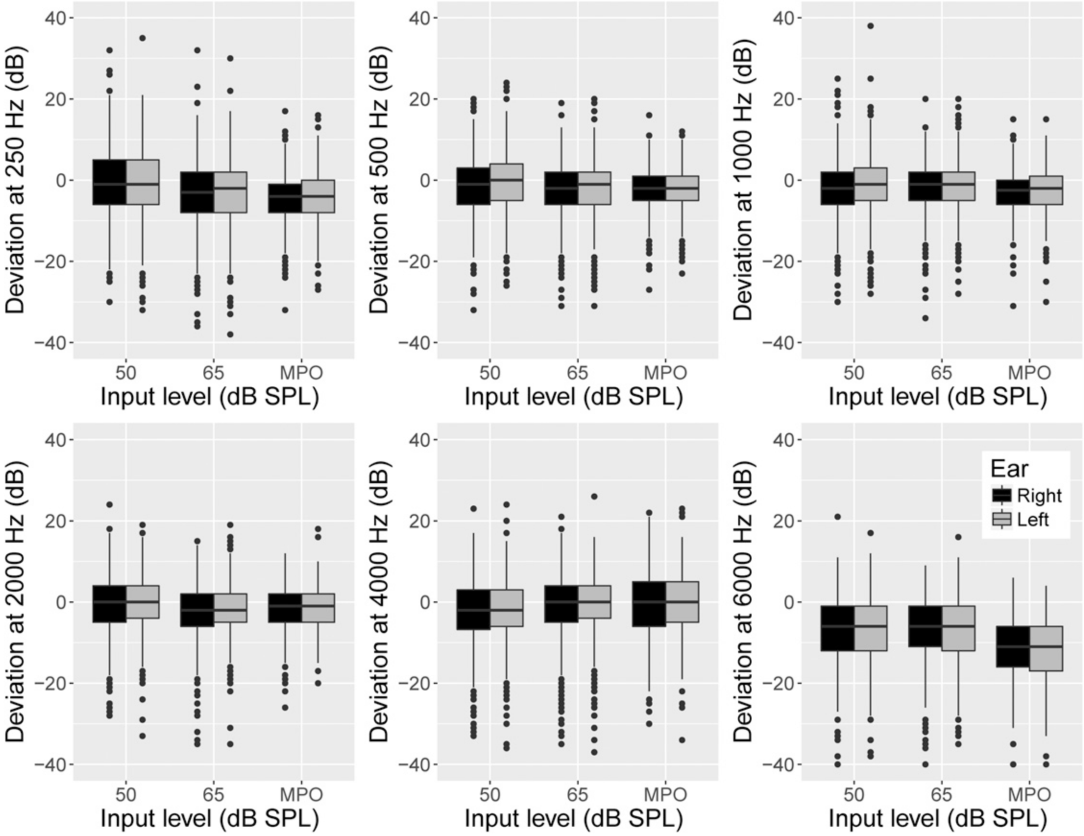

Figure 2. Absolute deviations from prescriptive target in dB as a function of frequency for soft speech (50 dB SPL), average speech (65 dB SPL), and MPO (85 dB SPL). Each panel represents a separate frequency. Black boxes represent right ears and gray boxes represent left ears. The boxes represent the interquartile range (25th–75th percentiles), the horizontal line across each bar represents the median and the whiskers represent the range of the 5th to 95th percentiles. Black circles represent individual data points that fall outside of the range of the 5th to 95th percentiles.

Table 4. Post Hoc Comparisons for Input Level by Frequency Interaction

Frequency (Hz)	Difference 65 – 50 dB	Difference MPO – 65 dB
500	**1.4 dB**	**2.0 dB**
1000	**2.9 dB**	**2.3 dB**
2000	**1.3 dB**	**2.5 dB**
4000	**4.2 dB**	**5.3 dB**
6000	**1.9 dB**	**- 2.1 dB**

Note: Bold numbers are significantly different based on post hoc test using Benjamini and Hochberg False Discovery Rate adjustment (1995).

all four frequencies, accounting for 51–68% of the variance in SL. This suggests that increased deviations from target reduce the SL for speech, even after accounting for variation related to differences in audiometric threshold.

Effects of Level- and Frequency-specific Deviations from Target on Speech Recognition

To examine the effects of level-dependent fitting errors on aided speech recognition abilities in quiet and in noise, differences in speech recognition for LNT-Hard in quiet and CASPA in noise were compared across groups based on the classification of their level-dependent fitting errors (Table 3). Owing to the small number of participants in some categories, participants were collapsed into four groups based on the number of levels where fitting errors >5 dB were observed: no deviations, one level >5 dB, two levels >5 dB, or all levels >5 dB. The resulting groups did not differ in terms of their better-ear pure-tone average based on a between-groups analysis of variance (ANOVA) ($F_{[3,605]} = 0.12$, $p = 0.947$, $\eta^2_p = 0.01$). Next, an ANOVA was completed for LNT-Hard in quiet and CASPA in noise across groups. Post hoc comparisons were completed using Dunnett's test, where the group with no deviations from prescriptive target served as the comparison group for each of the other groups.

Figure 4 shows LNT-Hard by fitting-error group. For LNT, the no-error group included 29 children, the single-level error group included 29 children, the two-level error group included 37 children, and the all-level error group included 26 children. The one-way ANOVA indicated significant differences in LNT-Hard percent-correct scores across groups ($F_{[3,117]} = 3.76$, $p = 0.013$, $\eta^2_p = 0.10$). The post hoc comparison indicated that the group with fitting errors at all input levels had 16.9%

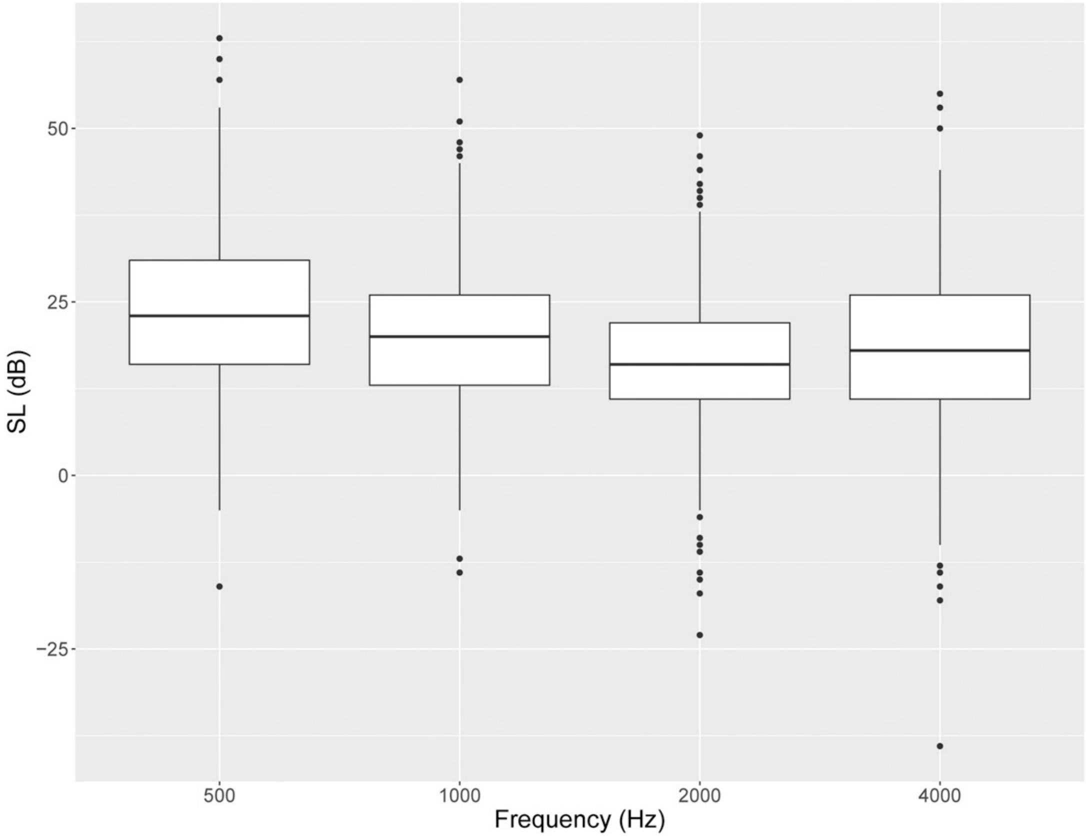

Figure 3. The SL for an average speech input level (65 dB SPL) across frequency for each child's better-fitted ear (the ear with the smallest RMS error for average speech). The boxes represent the interquartile range (25th–75th percentiles), the horizontal line across each bar represents the median and the whiskers represent the range of the 5th to 95th percentiles. Black circles represent individual data points that fall outside of the range of the 5th to 95th percentiles.

Table 5. Linear Regression Models for Sensation Level for Each Frequency

		Predictors	
	Adjusted R^2	Threshold	Fitting error
500 Hz	0.64, $p < 0.001$	$\beta = -0.69$, $p < 0.001$	$\beta = -0.37$, $p < 0.001$
1000 Hz	0.54, $p < 0.001$	$\beta = -0.60$, $p < 0.001$	$\beta = -0.38$, $p < 0.001$
2000 Hz	0.51, $p < 0.001$	$\beta = -0.49$, $p < 0.001$	$\beta = -0.45$, $p < 0.001$
4000 Hz	0.68, $p < 0.001$	$\beta = -0.63$, $p < 0.001$	$\beta = -0.40$, $p < 0.001$

Note: Threshold in dB SPL and fitting error as predictors of sensation level for each frequency in the better-fitted ear for each child.

lower scores than the group without fitting errors ($p = 0.004$). The groups with a single-level error and two-level errors were 9% ($p = 0.169$) and 6% ($p = 0.491$) lower on average than the no-error group, respectively, but these differences were not statistically significant.

Figure 5 shows CASPA scores for each group for the poorest SNR (−5 dB). A repeated-measures ANOVA was completed to assess differences in CASPA percent-correct phoneme recognition in noise across groups with SNR (−5, +10, and +20) as a within-subject factor. The no-errors group included 27 children, the single-level error group included 26 children, the two-level error group included 13 children, and the all-level error group included 17 children. The main effect of SNR was significant ($F_{[2,158]} = 520.9, p < 0.001, \eta^2_p = 0.87$), consistent with the expected pattern of increasing performance as SNR improved. Post hoc testing using false discovery rate revealed that significant differences were only observed between –5 dB and +10 dB ($p = 0.002$) and −5 dB and +20 dB ($p < 0.001$) as the aided phoneme recognition at +10 dB and +20 dB was near ceiling. The main effect of error group ($F_{[3,79]} = 0.21, p = 0.89, \eta^2_p = 0.008$) and the interaction of error group and SNR ($F_{[6,158]} = 0.9, p = 0.489, \eta^2_p = 0.03$) were not significant, indicating no significant differences in phoneme recognition in noise or pattern of performance across SNR based on the error groups.

To evaluate the effects of high-frequency audibility on speech recognition in quiet and in noise, the SL at 4 kHz was used to predict LNT-Hard monosyllabic word recognition in quiet and CASPA phoneme recognition in noise at the −5-dB SNR with linear regression. The −5-dB SNR condition for CASPA was selected for the regression analysis to avoid ceiling and floor effects, because the average performance in that condition was closest to 50% correct for each error group. Each participant's aided SII was included to control for variance in speech recognition related to broadband audibility. Sensation level at 4 kHz was included to estimate the additional effect of high-frequency audibility on speech recognition. For LNT-Hard recognition, the overall model was significant (adjusted $R^2 = 0.42$, $p < 0.001$). Higher aided SII ($\beta = 0.81$, $p < 0.001$) and higher 4 kHz SL ($\beta = 0.24$, $p = 0.03$) were associated with higher LNT-Hard percent correct in quiet. For CASPA recognition, the overall model was significant (adjusted $R^2 = 0.21$, $p < 0.001$). Consistent with the results from LNT-Hard recognition in quiet, higher aided SII ($\beta = 0.23$, $p = 0.04$) and higher 4 kHz SL ($\beta = 0.26$, $p = 0.02$) were associated with higher CASPA phoneme recognition at the −5-dB SNR.

DISCUSSION

The goal of the current study was to assess the extent to which children's HAs are fitted to provide audibility across a range of input levels and frequencies. In addition, the study sought to assess the impact of level- and frequency-dependent deviations in fitting from prescriptive target on aided speech recognition outcomes in quiet and in noise. Hearing aid verification and speech recognition data were collected from a large cohort of children who wear HAs. The key findings of the study were:

(1) Approximately 50–70% of children in the study had an RMS error for soft speech input levels (50 dB) that was >5 dB in at least one ear, compared with 40–65% for average speech input levels (65 dB SPL) and 40–50% for MPO. Only 34% of children in the study had HA fittings that were within 5 dB of prescriptive targets for soft and average speech and MPO for at least one study visit in their better-fitted ear. Whereas size of the RMS error decreased across visits as children got older, the percentage of children with fitting errors >5 dB RMS error did not change across study visits. Children with larger RMS errors had poorer aided audibility than peers with smaller RMS errors. Children with level-dependent deviations from prescriptive target had poorer word recognition in quiet than peers with fittings that were in closer proximity to prescriptive targets. Phoneme recognition in noise was not affected by group differences in level-dependent patterns of fitting error.

(2) Many children had limited audible bandwidth as measured by the SL at 4 kHz as the result of deviations from prescriptive target at 4 kHz and above. Increasing degree of high-frequency hearing loss and larger deviations from prescriptive target had

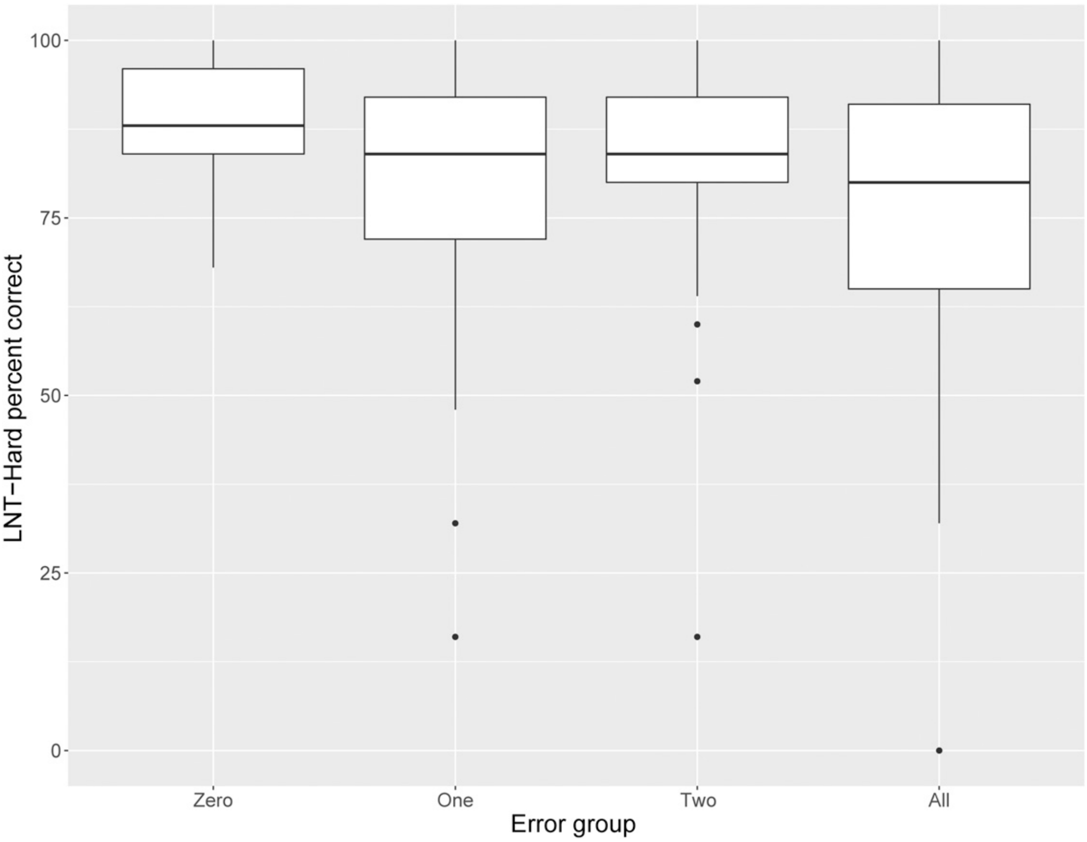

Figure 4. Percent correct for LNT-Hard in quiet for children with RMS errors >5 dB at zero, one, two, or all input levels. The boxes represent the interquartile range (25th–75th percentiles), the horizontal line across each bar represents the median, and the whiskers represent the range of the 5th to 95th percentiles. Black circles represent individual data points that fall outside of the range of the 5th to 95th percentiles.

> negative effects on the SL of speech at 4 kHz. Children with limited audible bandwidth through their HAs, because of deviations from prescriptive target and degree of hearing loss, had poorer aided speech recognition in quiet and in noise.

These findings represent an important extension of the existing literature on the effects of aided audibility and deviations from prescriptive targets. Specifically, the results provide a more detailed description of how HA fitting errors for specific input levels and frequency affect perception.

Prevalence of Level- and Frequency-dependent Deviations in Hearing Aid Fittings

Most children who wore HAs in the current study had significant deviations from prescriptive targets for their HA fittings. Only about one-third (34%) of children in the study had hearing aids that were fitted within 5-dB RMS error for soft speech, average speech, and MPO. Some previous studies based on average speech suggest that about half of children fitted with HAs have deviations from prescriptive target that are ≥5 dB for soft or average speech (McCreery et al, 2013) and that those deviations for average speech input levels persist over time (McCreery et al, 2015a). A study by Strauss and van Dijk (2008) found that only 25% of preschool children had HA fittings that approximated prescriptive targets at three or more frequencies for average speech. The current findings suggest that a majority of children who wear HAs do not have HAs that are optimized to allow audibility for speech at soft and average input levels. The RMS error for the fittings improved as children progressed through the study, but the number of children in the study with errors >5 dB did not change across the four study visits represented in this analysis.

The improvement in the proximity of the fittings to prescriptive target as the study progressed could have been related to several factors. As the cohort increased in age, verification practices shifted from simulated real-ear measures in the coupler with RECD to in situ measurements with the HA measured in the child's ear. This shift in verification methods could have increased the proximity of HA fittings to target over the course of the study. Alternatively, the improvement in the proximity of the fitting to prescriptive targets may have also been related to changes in audiologists'

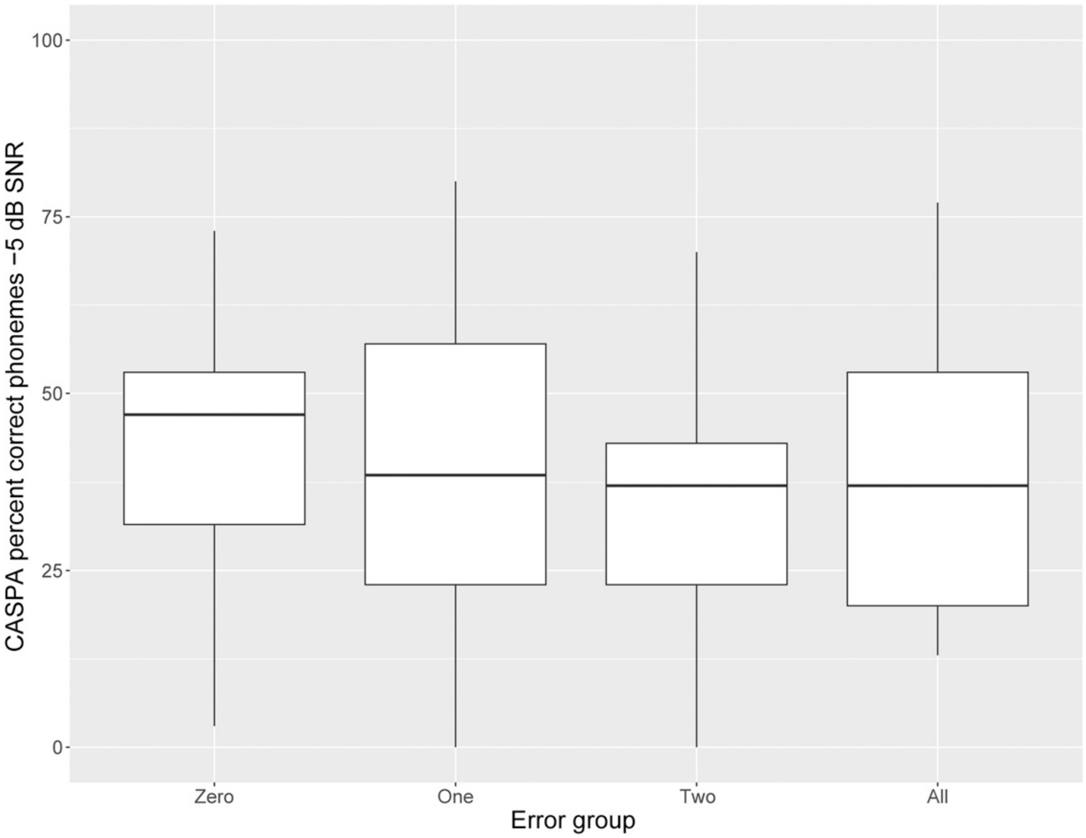

Figure 5. Percent correct for Computer-Assisted Speech Perception Assessment (CASPA) at a −5 dB SNR for children with RMS errors >5 dB at zero, one, two or all input levels. The boxes represent the interquartile range (25th–75th percentiles), the horizontal line across each bar represents the median, and the whiskers represent the range of the 5th to 95th percentiles.

verification practices during the course of the five-year study. Although the absolute proximity of the fittings improved over the course of the study, the percentage of children with RMS errors >5 dB did not shift appreciably. This suggests that any improvements in clinicians' fitting practices over the course of the study were insufficient to result in a clinically acceptable reduction in fitting errors. Furthermore, aided audibility did not increase across study visits, suggesting that any improvements in RMS error that occurred over the course of the study were insufficient to improve aided audibility for speech.

Across all study visits, 60–70% of children had deviations from prescriptive target >5 dB RMS for soft speech in at least one of their HAs. The greater likelihood of clinically significant deviations from the prescriptive target at soft levels than for average speech or MPO could occur for several reasons. One potential explanation is that clinicians who fitted the children with HAs may not be performing probe microphone verification of the HA output beyond average speech and MPO. Some clinicians may not be performing verification at all or may be using methods such as aided sound field thresholds that have been associated with larger deviations from prescriptive target (McCreery et al, 2013). The verification method used by the clinicians was not evaluated for the current study, so a definitive link between the fitting errors described here cannot be made.

The occurrence of deviations from prescriptive target that were >5 dB RMS was lowest for MPO. Approximately 40–50% of the children in the sample had deviations from prescriptive target >5 dB RMS for MPO for at least one visit. Similar to the previous study by Strauss and van Dijk (2008), average deviations from prescriptive target for MPO tended to be in the direction of fitting below prescriptive targets, potentially reflecting a conservative approach to setting the MPO for children who wear HAs or limited verification of the HA output beyond average speech. Interestingly, children with greater degrees of hearing loss were not more or less likely to have fittings that approximated prescriptive targets across multiple input levels than peers with milder degrees of hearing loss. The lack of differences in better-ear pure-tone average across error groups suggests that concerns about overamplification based on degree of hearing loss are not the only contributing factor to the level-dependent deviations from prescriptive target.

The frequency-specific deviations from prescriptive target were consistent with the high prevalence of deviations from prescriptive target based on the RMS error. Frequency-specific deviations from prescriptive target were highest for soft speech input levels and decreased as the input level increased. The magnitude of the deviations from target also increased as frequency increased with the most significant deviations at 4 and 6 kHz, consistent with recent data from Moodie et al (in press). The frequency-specific deviations from prescriptive target contributed to reduced SL at 500, 1000, 2000, and 4000 Hz, even after controlling for differences in SL related to degree of hearing loss. Children with larger RMS error from prescriptive target had poorer audibility for speech. The increased deviations from prescriptive target at higher frequencies may be related to limited high-frequency bandwidth of HAs in some cases (Kimlinger et al, 2015). However, the potential high-frequency bandwidth of HAs decreases as the degree of high-frequency hearing loss increases, and the deviation from prescriptive target had an additional influence on the SL at 4 kHz after controlling for the high-frequency threshold. This suggests that the audibility of speech could have potentially been further optimized at higher frequencies for some of the children in the study.

The high prevalence of level- and frequency-dependent deviations from prescriptive target observed in this sample has important clinical implications because of the potential to limit the benefit children received from their HAs. Prescriptive targets provide clinicians with a method of optimizing audibility for speech across a range of frequencies and input levels (Scollie et al, 2005). Poor aided audibility has been observed for children with larger deviations from prescriptive targets compared with peers with HAs fitted in closer proximity to prescriptive target (McCreery et al, 2013). These results suggest that further work needs to be done to implement protocols and procedures to ensure that HA verification is completed for a wide range of input levels. A recent study using data from the Ontario Infant Hearing Program (Moodie et al, in press) reported much smaller deviations from prescriptive target and better aided audibility than have been reported from the current cohort. The sample from the current study was collected from a wide range of localities in 17 states in the United States, where implementation of recommended fitting and verification protocols may be varied. The Ontario data were collected through the provincial health program where verification protocols and quality improvement programs are consistently used to improve the fitting practices of audiologists who serve infants and young children (Bagatto et al, 2010). This contrast between studies suggests that better fitting outcomes may be possible with the appropriate monitoring and support mechanisms.

As highlighted in another work by Moodie et al (2011), the existence of clinical practice guidelines that dictate best practices for pediatric HA verification is insufficient to encourage the implementation of these practices among practitioners. Alternatively, a systematic approach to knowledge translation may be more effective. Barriers to implementation of HA verification practices are likely to exist at multiple levels, including the clinical practice guideline, practitioner, workplace, and broader health system. A contextualized approach to integrating research findings related to pediatric HA outcomes may help to address these barriers more effectively than hierarchical models that simply mandate best practices through guidelines.

Effects of Level- and Frequency-dependent Deviations from Prescriptive Target on Aided Speech Recognition

A key prediction of the study was that level- and frequency-dependent deviations from prescriptive target would have a negative effect on aided speech recognition in quiet and in noise for children who wear HAs. This prediction was partially supported. Children were grouped based on varying degrees of level-dependent deviations from prescriptive target. Degree of hearing loss was not different between the resulting groups. For word recognition in quiet, children with deviations at soft and average speech inputs and MPO had poorer recognition than children with no significant deviations from target at any levels. Children with fittings that had ≥5 dB RMS errors for one or two levels were lower than the children without errors, but those differences were not statistically significant. For CASPA phoneme recognition in noise, there were no significant differences between groups based on the level-dependent differences in the deviations from prescriptive targets, which ran counter to the predictions of the study.

The discrepancy between results for error groups for speech in quiet and speech in noise could be explained by several factors. For speech in noise, reductions in audibility for soft input levels may not have led to additional decrements in performance because the speech cues at those levels were masked by the background noise. Therefore, the reduction in audibility for soft input levels might only be important when those cues are available to the listener as they are in quiet. In addition, whereas most of the deviations from prescriptive target were negative and of reduced audibility, the RMS error does not indicate whether the overall deviation from prescriptive target is positive or negative. As a result, some of the children in the error categories might have had greater audibility than the peers with more limited errors. The exact effect of overfitting is difficult to ascertain. For example, overfitting could have not only resulted in improved audibility but also increased distortion (Ching et al, 1998) or updward spread of masking (Scollie et al, 2005). In these ways, overfitting might have increased the variability of speech recognition performance in the groups with different configurations of fitting errors.

For frequency-specific errors, however, the negative effects of deviation from prescriptive target were more apparent. The SL of the long-term average speech spectrum at 4 kHz was used as a predictor of word recognition in quiet and phoneme recognition in noise while controlling for differences in aided audibility. Children with higher aided audibility for average speech had higher word recognition in quiet and phoneme recognition in noise, as expected. In addition, children with higher SLs at 4 kHz also had higher speech recognition in quiet and in noise than peers with lower SLs at 4 kHz, even after considering the influence of broadband audibility from the SII. This suggests that the reduction in audibility at 4 kHz from prescriptive target was significant enough to affect speech recognition in quiet and in background noise for children who wear HAs. This finding is consistent with earlier studies of speech perception (Stelmachowicz et al, 2001), phonological development (Moeller et al, 2007), word learning (Pittman, 2009), and morphosyntactic development (Koehlinger et al, 2015) that suggests that children with hearing loss who experience limited high-frequency bandwidth from their hearing aids may have delays in these domains. In some cases, frequency-dependent deviations from prescriptive target were present in children with overall RMS errors <5 dB, which highlights the importance of ensuring audibility at higher frequencies, even if the overall audibility meets the 5-dB RMS error criterion.

Limitations and Future Directions

This study was a longitudinal analysis of HA verification and aided speech recognition data from a large cohort of children, but is not without several notable limitations. Given the effects of frequency lowering on HA output, children with nonlinear frequency compression or other frequency lowering signal processing in their HAs were not included in this analysis despite the fact that this represents an increasing portion of the population of children who wear HAs. Although the study included data from more than 160 children who wore HAs, the numbers of children who contributed data for both verification data and speech recognition was considerably smaller. Larger samples may be needed to more accurately assess the impacts of specific level-dependent fitting-error patterns on speech recognition. Future studies may attempt to determine if the speech recognition deficits observed in this cohort extend to more distal outcomes in children with hearing loss, including language, academic, and cognitive domains.

CONCLUSIONS

This study examined the prevalence and impact of deviations from prescriptive targets for children who wear HAs. A majority of children in the study had significant deviations from prescriptive target, which were more prevalent for lower input levels and in the high frequencies. Children with deviations from prescriptive target across multiple input levels and at 4 kHz had poorer speech recognition in quiet and in noise than children with HAs fitted closer to prescriptive targets. These data support HA verification protocols that ensure the audibility of speech is quantified across a range of input levels and frequencies that will support speech recognition and other communication outcomes in children with hearing loss.

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