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Speech-in-Noise and Quality-of-Life Measures in School-Aged Children with Normal Hearing and with Unilateral Hearing Loss

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Abstract

Objectives: 1) Measure sentence recognition in co-located and spatially separated target and masker configurations in school-aged children with unilateral hearing loss (UHL) and with normal hearing (NH). 2) Compare self-reported hearing-related quality of life (QoL) scores in school-aged children with UHL and NH.

Design: Listeners were school-aged children (6–12 yrs) with permanent UHL ($n = 41$) or NH ($n = 35$) and adults with NH ($n = 23$). Sentence reception thresholds (SRTs) were measured using HINT-C sentences in quiet and in the presence of 2-talker child babble or a speech-shaped noise masker in target/masker spatial configurations: 0/0, 0/−60, 0/+60, or 0/±60 degrees azimuth. Maskers were presented at a fixed level of 55 dBA, while the level of the target sentences varied adaptively to estimate the SRT. Hearing-related QoL was measured using the Hearing Environments and Reflection on Quality of Life (HEAR-QL-26) questionnaire for child subjects.

Results: As a group, subjects with unaided UHL had higher (poorer) SRTs than age-matched peers with NH in all listening conditions. Effects of age, masker type, and spatial configuration of target and masker signals were found. Spatial release from masking was significantly reduced in conditions where the masker was directed toward UHL subjects' normal-hearing ear. Hearing-related QoL scores were significantly poorer in subjects with UHL compared to those with NH. Degree of UHL, as measured by four-frequency pure-tone average (PTA), was significantly correlated with SRTs only in the 2 conditions where the masker was directed towards subjects' normal-hearing ear, although the unaided Speech Intelligibility Index (SII) at 65 dB SPL was significantly correlated with SRTs in 4 conditions, some of which directed the masker to the impaired ear or both ears. Neither PTA nor unaided SII was correlated with QoL scores.

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Conclusions: As a group, school-aged children with UHL showed substantial reductions in masked speech perception and hearing-related QoL, irrespective of sex, laterality of hearing loss, and degree of hearing loss. While some children demonstrated normal or near-normal performance in certain listening conditions, a disproportionate number of thresholds fell in the poorest decile of the NH data. These findings add to the growing literature challenging the past assumption that one ear is “good enough.”

Keywords

unilateral hearing loss; pediatrics; sensorineural hearing loss; speech-in-noise; quality of life; single-sided deafness

INTRODUCTION

A growing body of research is challenging long-held assumptions that pediatric unilateral hearing loss (UHL) has minimal effects on a child's development (see Northern & Downs 1974, pg. 165). It is now well understood that children with UHL are at risk for academic underachievement, behavioral problems, psychosocial issues, and speech and language delays (Peckham & Sheridan 1976; Davis et al. 1981; Bess & Tharpe 1984; Bess et al. 1986; Culbertson & Gilbert 1986; Bovo et al. 1988; Oyler & et al. 1988; Jensen et al. 1989; Young et al. 1997; Watier-Launey et al. 1998; Kiese-Himmel 2002; Sedey et al. 2002; Borg et al. 2002; Most 2004; Martínez-Cruz et al. 2009; Lieu et al. 2010; Lieu 2013; Fischer & Lieu 2014). Several recent reviews of outcomes in children with UHL provide valuable summaries of what is currently known and demonstrate increased interest in understanding the abilities of and difficulties experienced by this population of children (Kuppler et al. 2013; Winiger et al. 2016; Krishnan & Van Hyfte 2016; Dornhoffer & Dornhoffer 2016; Rohlf et al. 2017; Anne et al. 2017). Although these articles have clearly established the deficits in global outcomes, fewer studies have focused on understanding the specific auditory problems experienced by this special population, which is imperative to inform intervention strategies. The current study examines the effects of permanent UHL of varying degrees and configurations on speech understanding in noisy listening environments and hearing-related quality of life (QoL).

Profound UHL results in exclusively monaural input to the central auditory system and therefore a loss of the advantages of binaural processing, such as sound localization and binaural release from masking. Despite the loss of binaural processing in children with profound UHL, physical head shadow effects can still create opportunities for spatial release from masking under some conditions. With signals of interest (targets) presented in front and unwanted (masking) sounds presented on the side of the poor ear, head shadow effects should in theory provide normal and useful signal-to-noise ratio (SNR) benefits at the good ear. Other spatial arrangements (e.g., targets on the side of the poor ear) are clearly not advantaged or are even seriously disadvantaged by head shadow, depending on the location of the masking sounds. When the target is presented from the front and maskers, with fluctuating amplitudes, from both sides, the ear with the better SNR is likely to change from moment to moment. Listeners with bilaterally normal hearing take advantage of those better short-term SNRs automatically and nearly optimally (e.g., Brungart & Iyer 2012). The

monaural listener, however, would clearly not experience this advantage during time segments when the better SNR occurs on the side of the severely impaired ear. Thus, there are specific target-masker spatial configurations in which significant impairments in speech perception can be logically predicted based on the audiogram alone and other spatial conditions where much smaller deficits would be predicted. This underscores the importance of evaluating auditory function in listeners with UHL across a variety of spatial configurations.

Listeners with UHL show auditory deficits mainly in sound localization and speech understanding in noise (e.g., Gatehouse & Cox 1972; Bess et al. 1986; Slattery III & Middlebrooks 1994; Ruscetta et al. 2005; Linstrom et al. 2009; Reeder et al. 2015). Speech perception studies in children with UHL have revealed poorer and more variable performance than peers with normal hearing (NH) even in the most favorable listening conditions (Bess, Tharpe and Gibler 1986; Bovo et al. 1988; Ruscetta et al. 2005; Reeder et al. 2015). For example, in the seminal study by Bess, Tharpe and Gibler (1986), 25 children (6–13 yrs) with UHL listened to nonsense syllables in quiet and in the presence of cafeteria noise. When compared to subjects with NH, listeners with UHL demonstrated poorer performance in all conditions, including quiet and when speech was directed toward the good ear and the masker toward the impaired ear, which have traditionally been considered optimal listening conditions for this population. In a more recent study by Reeder and colleagues (2015), 20 children (6–16 yrs) with UHL were tested on a variety of auditory tasks including word recognition in quiet and in noise, sentence recognition in diffuse noise, and sound localization. Children with UHL had poorer and more varied performance compared to normal-hearing, age-matched subjects on most of the tasks.

Existing studies of speech perception in children with UHL have typically included subjects with only the most severe degrees of UHL (e.g., Bess et al. 1986; Ruscetta et al. 2005; Reeder et al. 2015). With less severe degrees of unilateral losses, listeners should experience some degree of binaural hearing when sound levels are sufficient to exceed threshold in both ears. Binaural and spatial hearing abilities under these conditions of asymmetric inputs vary widely across subjects (Durlach et al. 1981; Häusler et al. 1983). Because of this, there is uncertainty regarding how children with milder degrees of UHL function auditorily and whether intervention for this population is warranted. Furthermore, most of the investigations to date have measured subjects' speech understanding using whole-word stimuli in the presence of noise maskers in a limited number of target-masker spatial configurations (e.g., Bess et al. 1986; Bovo et al. 1988). Fewer studies have investigated sentence recognition or employed real speech as maskers (Reeder et al. 2015; Corbin et al. 2017). This leaves questions about subjects' abilities in more challenging and realistic listening environments. The current investigation addressed some of these gaps in our knowledge by including children with a wide variety of hearing loss severity in the impaired ear and assessed auditory abilities using more ecologically valid tasks with a wider range of spatial conditions than some past research.

In the current study, we investigated sentence reception thresholds in the presence of either steady noise or child-generated speech. Spatial conditions included no separation between target and masker and 3 configurations with spatial separation to investigate if the children

benefited from realistic talker-masker locations. The experiment was conducted with school-aged children (6–12 yrs) with UHL. Because there are known developmental changes in speech recognition in noise during those years (e.g., Hall et al. 2002; Leibold & Buss 2013; Corbin et al. 2016), children with NH spanning that same age range also participated to serve as a comparison group. The current study characterized developmental trends in normal-hearing children, and children with UHL were compared to those norms. In addition to speech perception testing, a hearing-related QoL questionnaire, Hearing Environments and Reflection on Quality of Life (HEAR-QL-26, Umansky et al. 2011) was administered to children with UHL and NH and its relationship to speech-in-noise scores was examined.

MATERIALS AND METHODS

This study was approved by the Institutional Review Boards at the University of Massachusetts Amherst and Boston Children's Hospital.

Subjects

Ninety-nine native-English speakers were enrolled in the current study. Of these, 41 were children with UHL (20 females) and 35 were children with NH bilaterally (19 females). Child subjects ranged in age from 6 years;0 months to 12 years;11 months. An additional 23 participants were adults with NH (19 females), ranging in age from 19 to 57 years with a mean of 23 years. Subjects with NH were recruited from the University of Massachusetts Amherst student body and the greater Amherst and Boston, MA areas. Children with UHL were recruited from the patient population at Boston Children's Hospital, Boston, MA and UMass Memorial Medical Center, Worcester, MA.

All subjects received a comprehensive hearing test before participation in the study to confirm hearing status. Normal hearing was defined as thresholds ≤ 15 dB HL from 250–8000 Hz bilaterally. Unilateral hearing loss was defined generally following the guidelines set forth by the National Workshop on Mild and Unilateral Hearing Loss (2005): NH in 1 ear, defined as the average of air conduction (AC) thresholds from 250–8000 Hz ≤ 15 dB HL, with hearing loss in the other ear, defined as a pure tone average (PTA) of AC thresholds at 500, 1000, and 2000 Hz ≥ 20 dB HL or AC thresholds > 25 dB HL at 2 or more frequencies above 2000 Hz in the affected ear. Amongst the 41 children with UHL (see Table 1), 33 were unaided (no consistent device use within the past year with the exception of remote microphone hearing assistive technology in the classroom), while 8 were full-time users of a personal hearing device. The low number of aided subjects that we were able to recruit in the current study will be discussed later. The majority of hearing losses were sensorineural ($n = 37$), although 4 were of a mixed nature. Twenty-six hearing losses were congenital, while 15 were acquired. There were slightly more left-sided hearing losses ($n = 23$) in our sample compared to right-sided ($n=18$). Degree of hearing loss ranged from slight to profound, with an average 4-frequency PTA (0.5, 1, 2, and 4 kHz) = 67 dB HL. The most common etiology was unknown ($n = 22$), followed by abnormal inner ear anatomy ($n = 10$), and auditory nerve pathology ($n = 4$). Average age of hearing loss diagnosis was approximately 32 months (range = 0–132) for unaided subjects and 36 months (range = 0–120) for aided subjects.

As reported by subjects' parents, half of the participants with UHL ($n = 20$) were utilizing sound field or ear-level remote microphone hearing assistance technology (RM HAT) in the classroom at the time of the study. Of the 8 children who utilized a personal hearing device, 4 wore a traditional hearing aid on their impaired ear and 4 used an air conduction Contralateral Routing of Signal (CROS) system. Children who participated as aided subjects had at least 3 months of consistent device use. The average duration of device use was 21 months (range = 3 to 36 mo). The average time between hearing loss diagnosis and device fitting for aided subjects was 59 months (range = 9 to 101 mo).

Experimental Apparatus

Subjects were tested at 1 of 3 testing sites across the state of MA: The Center for Language, Speech, and Hearing at the University of Massachusetts Amherst, Amherst, MA, UMass Memorial Medical Center, Worcester, MA, and Boston Children's at Waltham, Waltham, MA. The same experimental hardware and software were used at all 3 testing sites. For auditory tasks, subjects were seated in the center of a double-walled sound-treated booth (see Appendix A for equipment specifications) and sat in a small wooden chair; seat height was measured 13 5/8" from the floor. Three loudspeakers (Yamaha MSP3 powered monitor speakers, 5.5" W $\times$ 9" L) were positioned 35 1/2" from the floor on speaker stands. Each individual subject's ear height was not measured. However, based on sitting height measurements from the literature (Fredriks 2005), the average ear height for 6-year-old children was likely 1 to 2 inches below the bottom of the loudspeakers, whereas the average height of 12-year-olds and adults was expected to be just above center of the woofer. The 3 loudspeakers were positioned 1 meter from the center of the subject's head, at angles of -60 (left), 0 (front), and $+60$ (right) degrees azimuth on the horizontal plane. Because the experimental apparatus was set up and broken down many times, permanent markings designating the placement of the chair and speaker stands were made on a canvas mat, which was rolled out before each experimental setup to ensure consistency between subjects. The assignment of the 3 physical loudspeakers to the 3 angles was random, so on any given set-up, loudspeaker A, for example, could be placed at -60 , 0 , or $+60$ degrees.

Custom Matlab software (MathWorks, Natick, MA) running on a laptop computer (MacBook Pro) inside the test booth controlled both stimulus presentation and scoring. The experimenter sat behind the subject in the test booth and maintained control of the computer program throughout the study, manually advancing experimental trials. Because the experimenter was responsible for advancing trials, she was able to ask for repetition or clarification from a subject as needed. The stimuli were retrieved from the computer's hard disk, converted to an analog signal by an external 8-channel 24-bit/ 96 kHz digital-to-analog (D/A) converter (ESI Gigaport HD+, Leonberg, Germany), and then sent to 1, 2, or all 3 of the previously described loudspeakers.

Experimental Design

1. Speech Recognition Experiment

Target Stimuli: Target stimuli consisted of the original recordings of all 16, 10-sentence practice and test lists from the Hearing In Noise Test - Children (HINT-C, Gelnett et al. 1995; Nilsson et al. 1994). The lists, which were recorded by an adult male talker, are

phonetically balanced and equated for naturalness, length, and intelligibility. An example sentence is “The ice cream is melting.” Sentences were copied from the manufacturer’s compact disc (CD) and stored on the computer’s hard drive. Sentences were later recalled by custom software and played at a resolution of 44100 Hz.

Masker Stimuli.: Two masker types were used in the current study: speech-spectrum noise (SSN) and 2-talker child babble (TTB). The SSN masker was taken directly from the HINT-C CD. This noise has the same average long-term frequency spectrum as approximately 2 minutes of continuous HINT sentences (approximately 72 sentences). For the TTB, one 10-year-old girl and one 10-year-old boy were digitally recorded speaking a series of nonsense sentences sampled at a rate of 44100 Hz. Sentences followed standard American English syntax, but were non-meaningful (e.g., “A shop will frame a dog,” Helfer 1997). Each talker’s recordings were stripped of their pauses, equated in rms level, and then added together to create 60 seconds of continuous TTB. A random selection of the masker was chosen before each presentation. The rationale for using an adult target and child-generated speech masker signals was to simulate common listening scenarios experienced in a classroom.

Procedure.: Each subject listened under 8 conditions (see Table 2), totaling 16 adaptive runs (15 experimental + 1 practice). The target signal (HINT-C sentence) was always presented from the front loudspeaker positioned at 0 degrees, while the masker signal (TTB or SSN) and masker location (0, +60, –60, or ± 60 degrees) varied. Both masker types were evaluated in all target-masker spatial configurations, with the exception of the symmetric masking condition (i.e., masker at ± 60 degrees) in which only the TTB masker was tested due to the limited number of HINT-C lists available. Because symmetrical presentation effectively eliminates head shadow advantages for the SSN masker over both long and short time windows and is also expected to substantially reduce binaural release from masking at low frequencies (van der Heijden and Trahiotis, 1999), differences between the symmetric SSN condition and the tested non-spatial SSN condition were expected to be quite small for both NH and UHL listeners. The position of the target and masker signals remained constant through the entirety of a run. On each trial, the masker preceded the initiation of the target sentence by 100 msec and ended simultaneously with the target sentence. After the completion of a run, the software automatically calculated the sentence reception threshold (SRT) according to the HINT-C protocol*, which estimates the SRT required for 50%-correct sentence understanding.

Maskers were presented at an overall rms level of 55 dBA, which was deemed a comfortable listening level. In the symmetrical masking configuration the 2-talker masker was separated; 1 interfering talker was presented from each of the side speakers at a level of 52 dBA. The first sentence in the adaptive run was presented either at –10 dB SNR for noisy conditions or 15 dBA for the quiet condition and was repeated at increasing levels until correctly

*For noisy conditions the presentation levels of sentences 5–10 and the level at which the 11th sentence would have been presented were averaged and then subtracted from the noise level. This calculation approximates the SNR (dB) at which the sentences were correctly identified 50% of the time. For the quiet condition, the presentation levels of sentences 5–10 and the level at which the 11th sentence would have been presented were simply averaged to find the SRT in quiet (dBA).

perceived. The subjects' task was to repeat back the target sentence; guessing was encouraged. Subjects' oral responses were judged for correctness by the experimenter. An incorrect response was anything less than 100% of the words correctly identified in each sentence. An exception to this rule was made for the first sentence in each run. Specifically, if all but 1 of the words in the sentence were correctly identified over 3 consecutive increasing presentation levels, the adaptive run proceeded as if the sentence was fully correct. It is possible that after subjects perceived the sentence one particular way they had fully primed themselves to continuing to perceive the sentence that way (Schacter & Buckner 1998). Using this approach avoided artificially high starting levels for the adaptive run. The level of subsequent sentences then varied adaptively in 2 dB steps; sentence level increased by 2 dB in instances of incorrect perception and decreased by 2 dB in instances of correct perception.

In noisy conditions, an average SRT was calculated from subjects' SRTs on 2 adaptive tracks. For the quiet condition, subjects listened to one 10-sentence list (see Table 2). The quiet condition was always run first, followed by a random presentation of the 7 unique noisy conditions. After a break, the subject produced a second SRT in each noisy condition, again presented in random order. Before experimental conditions, subjects listened to one 10-sentence adaptive HINT-C list in quiet to familiarize themselves with the task. This list was not used again during the experimental conditions.

Nilsson, et al. (1994) determined that the 95% confidence interval (CI) is ± 2.98 dB for SRTs when using one 10-sentence HINT list in quiet. When using two 10-sentence HINT lists in noise, the 95% CI is ± 1.49 for SRTs. To generate similar estimates of reliability of the thresholds obtained using our speech masker, 5 normal-hearing adult subjects who did not participate in the main experiment listened in the same condition (symmetric TTB masking) 16 times and produced 1 threshold run per test list. A grand mean was calculated for each subject by averaging the thresholds across the 16 runs. Because each threshold measured during the experiment was the mean of 2 threshold runs with random list assignments, every possible combination of 2 unique runs was averaged and subtracted from the grand mean, yielding a total of 1200 difference scores ($240 \text{ values} \times 5 \text{ subjects}$). Across the 1200 combinations, 95% were found to be within 1.9 dB of the subjects' grand mean.

2. Quality of Life—To assess pediatric subjects' QoL, we administered the HEAR-QL-26 questionnaire. This tool has been shown to be valid, reliable, and sensitive for children with both bilateral and UHL (Umansky et al. 2011). The HEAR-QL-26 is a 26-item questionnaire, appropriate for children 7–12 years old, which assesses 3 factors: perceived difficulty hearing in certain environments/situations (Environments), impact of hearing loss on social/sports activities (Activities), and impact of hearing loss on the child's feelings (Feelings). Children who routinely used a hearing device were instructed to answer the questions according to their hearing abilities with their device on. Children rated their responses on a 5-point Likert scale: Never (4), Almost Never (3), Sometimes (2), Often (1), or Almost Always (0). Scores were then transformed to a 0–100-point scale, where higher scores indicate a better hearing-related QoL. The overall HEAR-QL-26 score is computed as the sum of scores for items on each subscale divided by the number of items completed. The experimenter read each item aloud to subjects in a quiet room and recorded their responses.

RESULTS

Listeners with NH

Sentence Reception Thresholds.—Sentence reception thresholds (SRTs) for the subjects with NH are plotted below in Fig. 1 as a function of age in years for all conditions. The Front/Side data, shown in panels D and E, were the average of the results for the -60 and $+60$ degree masking conditions (4 thresholds in all, 2 from Front/Right and 2 from Front/Left). For child subjects with normal hearing, there were some small differences favoring the -60 degree (left) masker condition. These differences were, on average, 1.1 dB for SSN (which was statistically significant, $t(34) = 3.67$, $p = 0.001$), and 0.4 dB for TTB (non-significant, $p = 0.36$). These differences were statistically significant for the adults subjects and averaged 1.1 dB for SSN, $t(22) = 4.05$, $p = 0.001$, and 2 dB for TTB, $t(22) = 2.94$, $p = 0.008$. Repeated measurements in 1 of the audiometric sound booths used in the study revealed no identifiable acoustic basis for the asymmetry. It is possible that the lower thresholds measured in the presence of the left-directed maskers are related to the right-ear advantage seen frequently in the literature (Kimura 1967). The decision to average the data from the left and right masking conditions was based on the relatively small size of the differences and to help facilitate later comparisons to the data obtained from subjects with UHL.

The data shown in Fig. 1 reveal effects of age, masker type, and spatial configuration on SRTs. Considerable variability across subjects is evident, especially with the TTB masker. Developmental improvements in SRTs were observed in all conditions and appear well described by linear functions over the age range tested, shown by the solid lines through the data. The Pearson correlation coefficients, r , of the fitted lines are shown in Table 3. Based on these fitted functions, children's average thresholds obtained in SSN were adult-like (i.e., within 1 dB of adult values) by 12 years of age, while the thresholds obtained in TTB from 12-year olds were 2 dB or more poorer than adult values.

The NH reference lines without individual data points are replotted in Fig. 2A to allow for across-condition comparisons and in Fig. 2B to allow for more direct comparison of the slopes by normalizing the functions to the predicted SRTs of 6-year olds. Figures 2C and 2D show difference scores that help illustrate other trends in the data, described below. There were substantial differences in SRTs across the different masking conditions that exceeded any differences in age effects across conditions (i.e., there is no crossing of functions in Fig. 2A). The most difficult condition was co-located (Front/Front) SSN masking and the easiest was asymmetric (Front/Side) TTB masking, where thresholds were 6.8 to 9.6 dB better. Both masker type and spatial configuration contributed to this wide range of thresholds across conditions. Thresholds were better in the TTB masker than in continuous noise (see Fig. 2C), presumably because of spectrotemporal fluctuations in the masker that allowed glimpses of the target to be perceived at favorable SNRs (e.g., Festen and Plomp 1990, Brungart and Iyer, 2012). The spatially separated masking conditions likely produced better thresholds because of both binaural interaction and head shadow effects.

The normalized functions in Fig. 2B allow one to observe how age-related changes in performance varied across conditions. Thresholds improved relatively gradually in the co-

located (Front/Front) SSN masking condition, decreasing by only about 2 dB across the age span tested. For the co-located (Front/Front) TTB condition, thresholds improved at a much steeper rate, decreasing by approximately 5 dB over the same age range. The slopes of each function were compared statistically using the generalized estimated equations (GEE) approach (Zeger & Liang 1986). Bonferroni corrections were applied to account for multiple comparisons. The slope of the function for co-located SSN was significantly different from that for the co-located (Front/Front) TTB ($p < 0.001$) and asymmetric TTB ($p < 0.001$) conditions. All other pairwise comparisons were not significantly different. The steeper improvement with age for speech maskers relative to noise maskers is seen in Fig. 2C, where the SRTs with TTB versus SSN maskers is plotted as a function of age.

Spatial Effects.—As expected, spatial separation of target and masker also affected SRTs considerably. SRTs in co-located conditions minus those for spatial conditions provides a measure of spatial release from masking (SRM). For the asymmetric masking conditions, SRM was in the range of approximately 4 to 5 dB for both the SSN and TTB maskers over the age range (Fig. 2D, Table 4). Spatial release for the symmetric TTB masking condition was smaller (averaging 2 dB across age) than for the asymmetric conditions, as expected given the reduction in head shadow effects with maskers on both sides. There appeared to be an age effect on SRM for the symmetric condition, where the line shown in Fig. 2D estimates an SRM of 3.4 dB for 6 years olds that decreases to 1.3 dB for 12 year olds. However, confidence in this trend is not high, as the slope depends on the subtraction of the spatial and non-spatial lines in Fig. 2A, and the slope in the spatial condition, while significantly different from zero, has a low correlation coefficient (Table 3) as a result of the large variability in the data (Fig. 1). Additionally, across all subjects with NH, the adult child difference in SRM in this condition was minimal at 0.2 dB and not statistically significant ($p = 0.74$, see Table 4).

Listeners with UHL

Sentence reception thresholds.—SRT data from the subjects with UHL were compared to age-matched peers in the NH group. Before the age trends shown in Figs. 1 and 2 above could be used as normative data, it was necessary to characterize the variability in the NH thresholds. Because there were no obvious or consistent age trends in variability visible in Fig. 1, or in age-binned SDs, we computed 1 global SD for each listening condition, obtained from the square root of the mean of the squared deviations from the NH reference line for all 35 children with NH children (Eq. 1). The SDs obtained in this way closely matched the square root of the average variance of the individual age bins. As a further validation of the appropriateness of this approach, the percentage of data points from children with NH across all conditions that fell outside ± 1 SD was found to be 31%, almost exactly the 32% predicted by a normal distribution, and was not different at the edges of the functions (average of ages 6, 7, 11, 12 yrs = 31%) versus the middle range of ages (8, 9, 10 yrs = 32%).

$$SD = \sqrt{\frac{\sum (y_i - y')^2}{n}} \quad \text{Equation 1.}$$

where y_i , individual subject's SRT and y' , predicted SRT for the subject's age

Standardized scores were then calculated for each subject (Eq. 2), by subtracting the individual's score from the age-matched predicted score, then dividing the result by the previously calculated global SD. The resulting value represents the number of SDs from the NH reference line for an individual score.

$$\text{Standardized Score} = \frac{(y_i - y')}{SD} \quad \text{Equation 2.}$$

where y_i , individual subject's SRT and y' , predicted SRT for the subject's age

Several criteria were considered to compare the distributions of scores obtained between subjects with UHL and NH, including calculating the percentage of scores that were worse than the NH average (poorest 50%, assuming normality) as well as the percentage of scores falling in the poorest quartile (> 0.67 SD), 16% (> 1 SD), 10% (> 1.28 SD), and 2.5% (> 2 SD) of the NH data (see Ahmmed and Ahmmed, 2016 for a discussion of these issues). Each of these approaches would clearly demonstrate the same pattern of results -- more subjects with UHL than NH exceeding the chosen criterion. Ultimately our decision to use the bottom 10th percentile (poorest decile) was selected as a compromise. A focus on the bottom 2.5% (> 2 SD) could imply that one is only concerned about deficits in subjects with UHL when performance is poorer than that of virtually all NH children, whereas the bottom quartile seemed too lax to be considered "abnormal". Consequently, a Z-value of ± 1.28 SD was used as a cutoff to approximate the 90th and 10th percentiles in the NH data, consistent with approaches taken in previous studies (e.g., Ahmmed, 2017).

SRT values for the children with UHL are plotted in Fig. 3 for all listening conditions as a function of age in years. Children with unaided UHL are represented in the figure by unfilled circles, whereas children with aided UHL are denoted by their subject ID previously listed in Table 1 (C for CROS aid, H for traditional hearing aid). Given the small number of subjects utilizing CROS and traditional hearing aids, statistical testing was not performed on these 2 small subject groups and their data were not included within the larger group of children with unaided UHL.

Scores falling inside the 10th and 90th percentile boundaries (dashed lines in Fig. 3), indicate subjects with UHL who performed within ± 1.28 SD of the predicted NH score, whereas scores falling above the dashed lines indicate subjects with UHL who were performing > 1.28 SD poorer than predicted levels (approximately the poorest decile). Thresholds within the UHL group varied greatly, with some subjects falling within, many falling above, and a few below this range of performance of NH subjects.

Despite the variability observed in the UHL dataset there were notable similarities to the data obtained from subjects with NH. Firstly, the overall developmental trends in the raw SRT values obtained from subjects with UHL appear to be similar to those observed with NH controls (see Fig. 3). Secondly, similarities between the 2 data sets are evident in comparisons of SRTs across masker types. For example, like NH listeners, subjects with

UHL on average had lower (better) thresholds in the presence of the TTB masker compared to the SSN masker.

Clear effects of target/masker spatial configuration on SRTs are also observed in Fig 3. Predictably, performance was noticeably poorest in conditions when the masker was at the side of the subjects' normal-hearing ear (see Fig. 3 F,G). The average SRTs for subjects with UHL were about 7 and 6 dB poorer than the NH reference in this Front/Normal configuration for TTB and SSN maskers, respectively (see Table 5). Somewhat unexpected, however, was the number of subjects who fell into the poorest decile of the NH data in the opposing configuration, with the masker directed to the poorer-hearing ear (Front/Impaired, Fig. 3 D,E). The average SRT for subjects with UHL was about 2 dB poorer than the NH reference even in this more favorable listening condition (see Table 5).

The percentage of SRTs falling ± 1.28 SD from the NH reference for each condition was calculated for subjects with NH ($n=35$) and unaided UHL ($n=33$) and are plotted below in Fig. 4. Based on the statistics of a normal distribution, the number of NH subjects meeting this criterion was expected to average 10% (3.5 children), and instead averaged closer to 2.5 children across conditions. To be conservative, we still used the expected value from a normal distribution as the criterion for UHL subjects falling into the bottom NH decile. Not surprisingly (from Fig. 3), the percentage of listeners with UHL having thresholds in the poorest NH decile was high and depended heavily on the listening condition. When the masker was presented only on the side of the normal ear (Front/Normal), 88% and 94% of subjects with UHL had scores in the poorest decile, for the TTB and SSN masker, respectively. Although notably better in the opposite condition, Front/Impaired, where head shadow should be advantageous, more than 40% of subjects (42% for SSN and 45% for TTB) still had scores in the poorest decile. Even for those conditions where no spatial cues were present (e.g., Quiet and Front/Front), a substantial percentage of subjects with UHL scored in the poorest decile (33.3% for Quiet, 45.5% for Front/Front - TTB). For 6 of the 8 conditions, more than 40% subjects with UHL had scores falling in the bottom 10th percentile (see Fig. 4). All subjects with UHL had at least 1 score falling in the poorest decile, with more than half of subjects (18/33) obtaining scores in the poorest decile in at least half of the listening conditions. In contrast, none of the 35 children with NH had more than 2 thresholds in the lowest decile. Chi-squared tests were performed to statistically compare the proportion of scores in the poorest decile between subject groups (UHL vs. NH) for each listening condition. Statistically significant differences between subject groups were found for all listening conditions, except Front/Front – SSN (see Fig. 4).

In Fig. 3 the data points for the 8 aided subjects seem to generally fall amongst those of the unaided subjects. When collapsed across all conditions, 25 of the 32 (78%) SRT data points provided by the 4 CROS users (4 subjects $\times$ 8 conditions), fell in the poorest decile. Among the 4 subjects who used a traditional hearing aid, 17 of the 32 (53%) SRT data points fell in the poorest decile. These can be compared to the data provided by the unaided subjects where 138 of the 264 data points (52%) met the same criterion. Given the small number of subjects using hearing devices, the fact that CROS users tended to have poorer PTAs than HA users, and the fact that we do not have unaided speech thresholds from the same subjects, the trends noted above should be considered with caution.

Correlations.—Further analyses were computed on the threshold deviations (i.e., number of dB from the age-matched score taken from the NH reference lines) to determine whether masked sentence recognition performance, for each listening condition, was associated with specific patient variables, such as degree of hearing loss in the impaired ear, unaided speech intelligibility index (SII) at 65 dB SPL in the impaired ear, sex, or laterality of hearing loss. No significant differences in SRT deviations were found between male and females, nor right- vs. left-sided hearing losses. The Pearson correlation between degree of hearing loss (4-frequency PTA 0.5, 1, 2, 4 kHz) and SRT deviations for subjects with unaided UHL was not statistically significant except in the target-spatial configurations Front/Normal – SSN ($p < 0.001$) and Front/Normal – TTB ($p < 0.001$), see Fig. 5. However, estimated SII, as computed by the Verifit2 system at 65 dB SPL input, appeared to be more sensitive, correlating to SRT deviations in half of the conditions. There was a statistically significant negative Spearman correlation between unaided SII and SRT deviations for subjects with unaided UHL in the following listening conditions: Front/Impaired – TTB ($p = 0.04$), Front/Normal – TTB ($p < 0.001$), Front/Normal – SSN ($p < 0.001$), and Front/Impaired & Normal – TTB ($p = 0.007$).

Spatial Effects.—Average SRM values (SRT in co-located conditions minus spatial conditions) for subjects with unaided UHL and individual values for the 8 subjects who used a hearing device are reported below in Table. 6. Average SRM for subjects with unaided UHL was within 1 dB of that obtained by NH child subjects for both TTB and SSN maskers when they were presented to the side of the impaired ear (although this difference was statistically significant in the case of the SSN masker). However, listeners with UHL demonstrated effectively no SRM, on average, in the conditions where masking was directed toward the normal ear and less than 1 dB SRM was obtained when the masker was presented from both sides (see Table 6).

Given the small number of aided subjects it is difficult to characterize their SRM benefit by hearing device type. For traditional hearing aid users, the SRM values from Table 6 are distributed on both sides of the means for unaided listeners, shown in the second row of the table, with 10 values above and 10 below the unaided means. Somewhat encouraging is that positive SRM values were observed for all traditional hearing aid users in condition Front/Impaired for both masker types. Furthermore, individual subjects H1 and H3 demonstrated particularly encouraging performance, with positive SRM values across all listening conditions. For the CROS users, most (15/20) of the SRM values shown in the table were poorer than the unaided means. These differences observed between subject groups should be interpreted with caution given the small sample sizes.

Quality of Life

Following speech perception testing, hearing-related quality of life (QoL) was assessed in pediatric subjects using the HEAR-QL-26. The HEAR-QL-26 was intended for use with children aged 7 to 12 years old; however, it was administered to all of our subjects. It was determined that not all of our 6-year-old subjects were able to perform the rating task reliably. If any responses from 6-year-old subjects were deemed inconsistent and unreliable, results from those subjects were excluded from the final analysis ($n = 4$). An example of

inconsistent responses would be if a child responded “Almost Always” to the question “Does your hearing make you feel different from everyone else?” but responded “Never” to the question “Do you feel different from others because of your hearing?” The final analysis includes 32 children with NH and 32 children with unaided UHL.

QoL scores for each pediatric subject are displayed in Fig. 6 for each subscale as well as the total score on the HEAR-QL-26. Box plots are overlaid on the individual subject data; grey and white boxes highlight the distribution of scores for subjects with NH and unaided UHL, respectively. Poorer and more variable scores are easily observed within the unaided UHL subject group compared to subjects with NH. Independent-samples t-tests were performed to compare mean QoL scores (displayed as + symbol in Fig. 6) between subjects with unaided UHL and their peers with NH; a significant difference between scores was found on the Environments subscale, $t(62)=5.7$, $p < 0.001$, Activities subscale, $t(62)=3.2$, $p = 0.002$, Feelings subscale, $t(62)=4.5$, $p < 0.001$, as well as the Total score, $t(62)=6.0$, $p < 0.001$ (see Fig. 6). Quality of life scores for children with UHL were the lowest on the Environments subscale, which targets how subjects’ hearing loss affects their perceived ability to listen in adverse listening environments such as classrooms, restaurants, during gym class, and at recess. The Feelings subscale had the second lowest QoL score for subjects with UHL. This subscale addresses subjects’ emotional response to hearing loss. For example, does their hearing loss make them feel angry, nervous, anxious, timid, or simply different from others? The smallest, yet still significant, difference between subjects with NH and UHL was observed on the Activities subscale, which addresses how a subject’s hearing loss affects their social engagement with their peers. Hearing-related QoL scores were not correlated with degree of hearing loss in the impaired ear, unaided SII, SRT performance, nor SRM in any listening condition.

The current data can be viewed in relation to those obtained by Umansky et al. (2011) who compared HEAR-QL-26 scores for 35 children with UHL to 35 children with NH; mean values from Umansky et al. (2011) are displayed in Fig. 6 (see U symbols) for reference. There were differences in both the subject population and how the HEAR-QL-26 was administered across studies, which may account for the somewhat higher QoL scores reported in the Umansky’s et al. (2011) sample of children with normal hearing. However, the differences between children with UHL and NH are well replicated.

The aided subjects are also shown in Fig. 6 for reference (H1, H2, H4 denote subjects who wore hearing aids, C1–C4 denote subjects who wore CROS hearing aid systems). Although there are too few subjects to make definitive conclusions, it is interesting to note that in the Environments and Feelings subscales, as well as the Total score, all 3 children using a traditional hearing aid (one 6-yr-old was excluded) reported notably higher QoL values than the mean of the subjects with unilateral hearing loss who were unaided.

DISCUSSION

Effects of Age

Sentence reception thresholds (SRTs) improved with increasing age in all listening conditions for both NH and UHL subjects, with NH subjects reaching or approaching adult-

like performance by 12 years of age in most conditions. These findings are consistent with the developmental literature in this area showing that younger children require higher SNRs than older children to perform similarly on speech-in-noise tasks (e.g., Elliott 1979; Corbin et al. 2016). Several studies conducted in other laboratories (e.g., Leibold & Buss 2013; Baker et al. 2014; Corbin et al. 2016) have plotted age on a logarithmic axis. Some of the improvements appear linear on that scale over substantial portions of the school age range, suggesting a non-linear improvement in thresholds with years of age. The improvement in SRT for NH subjects in the current study, however, was reasonably well described by linear functions for all conditions, with steeper growth for comparable conditions when testing was conducted in the presence of the TTB than in SSN. This latter result is consistent with several published studies demonstrating a steeper developmental trajectory with a speech masker compared to a noise masker (e.g., Leibold & Buss 2013; Corbin et al. 2016).

Across all listening conditions, children with unaided UHL appeared to follow similar developmental trajectories, but had average SRT deficits ranging from approximately 1–7 dB compared to age-matched peers with NH (see Table 5). Measurements of the HINT performance/intensity functions indicate that a 1 dB change in SRT produces on average approximately a 10-percentage point shift in sentence intelligibility in continuous noise (Soli & Wong 2008). Thus, to the extent that the HINT-C presented in noise has similar properties to the HINT (the sentences are a subset of the HINT), average deficits in sentence intelligibility at a fixed SNR for conditions with SSN masking were estimated to range from as little as perhaps 8 percentage points in the Front/Front condition to as much as 60 or more percentage points in the Front/Normal condition. The somewhat more gradual psychometric function slopes for speech presented in speech babble (Wilson et al. 1990) would predict smaller, but still substantial, deficits in intelligibility at a given SNR. Although there was considerable variability in the scores within the UHL group, a disproportionate number of thresholds fell in the poorest decile of the NH data (see Fig. 4).

Effects of Masker Type

In the current study the TTB masker was less effective than the SSN masker for both UHL and NH listeners, producing consistently lower thresholds (Fig. 2). Recall that the masking speech was spoken by children and the target speech by an adult male in an attempt to simulate possible listening scenarios experienced in a classroom. Improved performance with the TTB masker is expected to some extent because a speech masker with just 1 or 2 talkers contains temporal and spectral fluctuations that allow glimpses of the target at favorable SNRs and indeed a difference in this direction has been reported in the literature (e.g., Duquesnoy 1983; Festen & Plomp 1986; Edmonds & Culling 2005). However, differences in the opposite direction have also been reported (e.g., Carhart et al. 1975; Freyman et al. 2001; Leibold & Buss 2013; Corbin et al. 2016) particularly in conditions without target-masker spatial separation or in children when the masker is continuous as opposed to gated (Hall et al. 2002). This observation is likely linked to confusions between target and masker that add a “perceptual” or “informational” component to the masking effect. In the current study, the potential for confusability of the adult and child talkers was low based on expected differences in the acoustic properties of their voices (e.g., fundamental and formant frequencies). Further, if there was a distracting element to the

presence of children's voices, it did not appear to affect the current listeners to the extent that it made the 2-talker masker more difficult than the SSN masker.

Across all 3 spatial configurations where it was measured, average deficits in SRTs for UHL subjects were greater in the TTB masker than the SSN masker by approximately 0.5 to 1 dB (Table 5). In this section we focus on the differences from NH subjects, and across the two masker types, in the non-spatial Front-Front condition. For the SSN masker, thresholds from UHL subjects averaged just 0.78 dB above the NH reference line (Table 5), with thresholds from only 6 (18%) of the subjects falling in the poorest decile. The literature on binaural summation of tones in noise suggests little reason to expect even a slight advantage for those with 2 normal ears. For example, there is no measurable binaural advantage in the relevant diotic (known as NoSo) versus monaural (known as NmSm) masked detection conditions for pure tones in continuous noise (Egan 1965; Langhans & Kohlrausch 1992). Yet, in agreement with our slightly elevated SRTs, data from Reeder et al. (2015) and Bess et al. (1986) showed poorer speech recognition performance in children with UHL in non-spatial conditions (e.g., Front/Front). Adults also show improvements on the order of 1 or 2 dB in speech reception thresholds in noise for binaural relative to monaural listening in co-located target/masker conditions (e.g., MacKeith & Coles 1971; Plomp 1976). We are unaware of any widely accepted explanation for these elevated thresholds, but it is worth noting that the Egan (1965) and Langhans and Kohlrausch (1992) data showing no binaural benefits are for masked *detection* threshold, whereas speech reception thresholds are expected to be several dB above detection threshold.

For the Front/Front configuration with a competing speech masker, the current data show a larger and statistically significant deficit in subjects with unaided UHL, relative to peers with NH, averaging almost 2 dB (see Table 5). Fifteen children with UHL (45%, see Fig. 4), were in the bottom decile. This more substantial deficit agrees with data from Plomp (1976) and Bronkhorst and Plomp (1989), who measured a larger binaural advantage in competing speech than in competing noise for front-front targets and maskers. The larger deficit observed across these studies in competing speech relative to competing noise could suggest that some listeners with UHL (or NH subjects listening monaurally) are on average less able to take advantage of the temporal-spectral fluctuations in the masker to the same extent as bilaterally NH subjects. A second possibility is that, if the importance of having 2 normal ears increases above detection threshold, the degree to which the speech signal was above detection threshold is most certainly greater for the TTB masker with its inherent fluctuations. A third possibility is that larger deficits with the speech masker observed in these studies are a byproduct of the more gradual psychometric functions found with recognition in the presence of speech maskers than noise maskers (Wilson et al. 1990). The more gradual slopes lead to a larger deficit in decibels for the same performance difference measured in percent correct.

Effects of Spatial Configuration

Children with NH performed better in all spatially separated target/masker conditions as opposed to co-located conditions with both masker types. The amount of spatial release from masking (SRM) depended on the listening condition and age of the subject. In the

asymmetric masking configurations, SRM was about 5 dB when averaged across age, which is consistent with previous studies (e.g., Litovsky 2005; Murphy et al. 2011; Lovett et al. 2012). Despite there being no long-term SNR advantage with the symmetrically placed TTB masker, most subjects appeared able to exploit better ear glimpses that vary from ear-to-ear temporally, obtaining on average 2 dB of SRM in this condition, which is comparable to the 2.75 dB SRM found in children with NH (mean age = 7 yrs) by Ching et al. (2011) in a similar symmetrical masking configuration.

There were acoustic and possibly psychoacoustic bases for expecting at least some developmental increases in SRM. The acoustic bases included increases in interaural time and level differences from slight average head size growth over the age range tested (Nellhaus 1968) and a possible slightly more advantageous ear height relative to the loudspeakers with increasing age, as described in the Methods. The relevant psychoacoustic finding is that binaural release from masking measured with headphones (No π versus NoSo) has been shown to increase slightly with age over this range in a subset of specific conditions tested (see Hall et al., 2004). Despite these reasons for potentially observing greater SRM with age, trends in this direction were not strong or consistent across masking conditions (Fig. 2D). The finding of little developmental effect on SRM is consistent with previous studies (e.g., Litovsky 2005; Garadat & Litovsky 2007; Ching et al. 2011; Murphy et al. 2011; Misurelli & Litovsky 2012; Lovett et al. 2012).

For listeners with UHL, SRTs were poorest relative to those from NH listeners when the masking signal was directed towards UHL subjects' normal-hearing ear (Front/Normal, see Fig. 3F,G), a predictable result given that this condition decreases the SNR in the ear with better hearing. Almost all the subjects with UHL fell in the poorest decile (Fig. 4) and SRM was essentially non-existent in this condition (see Table 6). These findings are consistent with previous speech perception studies in listeners with UHL demonstrating poorest performance when the masker is directed towards the subject's better-hearing ear (e.g., Bess et al. 1986; Rothpletz et al. 2012; Reeder et al. 2015). SRM for UHL subjects was also near zero in the symmetrical masking (TTB) condition. Despite the relatively high variability in the NH data for this condition, more than half of subjects with UHL (52%, see Fig. 4) had thresholds in the poorest decile of the NH data.

In the target/masker spatial configuration Front/Impaired, physical head shadow effects work in UHL subjects' favor to improve SNRs at the normal-hearing ear to the same extent expected for bilaterally NH peers. Results of the current study for these conditions are consistent with previous studies showing better performance when the masker is adjacent to subjects' impaired versus normal ear (e.g., Bess et al. 1986; Reeder et al. 2015; Corbin et al. 2017). Yet a substantial number of children with UHL in the current study (>40%, see Fig. 4) had thresholds in the poorest decile of the NH data even in this more favorable configuration. This trend is consistent with data from the existing literature (e.g., Bess et al. 1986; Ruscetta et al. 2005; Reeder et al. 2015) demonstrating auditory deficits in children with UHL even in the most advantageous listening conditions.

Most of the deficits in the Front/Impaired condition are likely to be due to whatever caused the deficits in the Front/Front condition, as average SRM was only 1 dB worse than for NH

subjects with the SSN masker, and was essentially the same for the TTB masker. Findings are consistent with those obtained by Corbin, et al. (2017) who evaluated SRM in child and adult subjects with simulated conductive UHL. Corbin et al. (2017) measured SRM using speech-shaped noise and 2-talker speech maskers in 3 target-masker spatial configurations: Front/Front, Front/Impaired and Front/Normal. Akin to the current results, SRM was measurable only when the masker was directed exclusively to the side of the impaired ear (see Fig. 2 in Corbin et al. 2017).

Performance of Subjects Wearing Hearing Devices

The SRTs from the few subjects who wore traditional or CROS hearing aids are not easily distinguished as being better as those of the unaided subjects in Figs. 3 and 5. For the children with traditional aids, amplification would effectively decrease audiometric thresholds in the poorer ear (i.e., provide an improvement in audibility). In many conditions, subjects with less hearing loss did not have much better SRTs than those with more severe loss (see Fig. 5). Therefore, it is difficult to make a straightforward prediction that amplification should improve SRTs. For the 2 conditions with the strongest relationship between SRT and UHL severity (i.e., Front/Normal, both masker types), there was a greater reason to expect that traditional hearing aids would be helpful. The benefit would have been seen with lower SRTs relative to what is estimated from the fitted line for their given degree of unaided hearing loss. But with the current group design and small number of aided subjects, all of whom were fitted late, there is not sufficient information to make judgments about the efficacy of traditional hearing aids, only that the data from these few subjects do not stand out as being different from the unaided subjects with the same degree of hearing loss. Whether some benefits would have been observed in a within-subjects' comparison of unaided and aided speech reception thresholds is unknown. For the 4 subjects wearing CROS aids, most of the SRT data were also not easily distinguished from those obtained from the unaided listeners. It should be noted that the optimum condition to demonstrate benefit from CROS aids, with the target speech presented to the side of the poorer ear, was not tested in this study, as the focus was on noisy conditions that included a front target position.

SRM values varied widely (see Table 6) across conditions and type of aid (traditional versus CROS) and across the 4 listeners within these categories. It is well understood that CROS technology does not restore binaural hearing function and, unsurprisingly, most SRM values were smaller than the mean SRM obtained by the unaided UHL group. CROS technology allows improved access to sound on the side of the impaired ear, which is beneficial when those sounds are of interest to the listener, such as a teacher's voice, but can also be detrimental to speech understanding if those sounds are noise or competing speech, as was observed in the current study. This smaller SRM measured in CROS users should be explored further through a within-subjects study design where unaided and aided performance can be compared in the same subjects.

A somewhat more encouraging finding is that there were 2 subjects (H1 and H3) among the 4 traditional hearing aid users who demonstrated SRM in all listening conditions. It is important to note that the average time between hearing loss diagnosis and hearing aid

fitting in the current traditional hearing aid sample was 54 months (mean age at hearing aid fitting = 5 yrs). It is possible, but we cannot be certain given the lack of subjects with UHL who were fit in infancy, that some of the traditional hearing aid users in the current study missed a sensitive period for bilateral input, limiting the amount of potential benefit to be gained from traditional hearing aids (Gordon et al. 2013). Further, evidence is emerging that auditory experience may be an important factor in the development of perceptual abilities related to speech segregation (see Leibold 2017 for a review). It is reasonable to question whether performance would have been better had this sample received more timely intervention.

Quality of Life

Quality of life (QoL) measures may prove to be a useful tool to assess daily function in children with UHL. In the current study, subjects with UHL had significantly poorer self-reported, hearing-related QoL than NH controls. Differences between the 2 groups were greatest on the Environments subscale, indicating substantial difficulty hearing in complex listening environments (e.g., gym class, restaurants, outside, etc.). Umansky et al. (2011) defined poor quality of life to be a total HEAR-QL-26 score ≤ 70 . In the current study, 14/33 subjects with unaided UHL, 2/4 subjects using a CROS and 1/4 subject using a traditional hearing aid had total scores below this criterion. Encouragingly, past research has demonstrated improved quality of life for children with UHL through the use of conventional amplification (Briggs et al. 2011). The results from our 3 subjects utilizing a traditional hearing aid are not inconsistent with this finding. Decreased QoL scores are consistent with previous reports of adults with unilateral sensorineural hearing loss reporting feelings of embarrassment, annoyance, confusion, and helplessness (Giolas & Wark 1967) and are in line with pediatric data collected by Umansky, et al. (2011). Of further note, scores on the HEAR-QL were not correlated to degree of UHL nor unaided SII. Findings are consistent with previous reports of weak relationships with pure-tone sensitivity and self-reported hearing handicap (Newman et al. 1990). Such findings emphasize the overall impact of what is widely considered a minimal hearing loss and suggest the need for support.

Clinical Considerations

The fact that it was much easier to identify and recruit children with UHL who were unaided than aided in our recruitment area, which included Western, Central, and Eastern Massachusetts, could suggest that current recommendations for intervention with wearable prostheses may not be very aggressive in these regions. Interestingly, the rate of traditional hearing aid use in the current study sample (4/41, 10%) is close to the rate observed nationally in 1997 (57/423, 13%, English & Church 1999) suggesting that practice management and/or patient acceptance of hearing aids has largely remained unchanged in this population. On the other hand, the rate of remote microphone hearing assistance technology (RM HAT) use, such as frequency modulation systems, increased from 17% (English & Church 1999) to 49% (current study) over this same time period. As demonstrated in the current study, many children with UHL may require substantial increases in the SNR to achieve the same level of auditory performance as their peers with NH. These findings continue to support the recommendation for routine use of RM HAT for

children with UHL to help improve the SNR in challenging listening environments (Cincinnati Children's Hospital Medical Center 2009; American Academy of Audiology 2013; Bagatto & Scollie 2014).

Given the significance of masker location on speech recognition performance in listeners with UHL, consideration should be taken regarding target-masker spatial configuration(s) employed during audiological assessment. A recent consensus statement published by Van de Heyning et al. (2016) recommended evaluating hearing device benefit in adult patients with single-sided deafness in the following target/masker spatial configurations: Front/Front, Front/Impaired, and Impaired/Normal, in order to quantify binaural summation, squelch, and head shadow, respectively, in both aided and unaided conditions. Evaluation of multiple target-masker spatial configurations should also be considered in the evaluation of pediatric patients in order to describe any deficits and/or potential treatment effects across a range of realistic conditions (Firszt et al. 2017). A narrower approach, for example, verifying the benefit of a rerouting device only in the primary condition it was designed to help with, could lead to a skewed picture of the device's benefits as it ignores situations in which it may actually result in poorer performance than in the unaided condition. Evaluating patients with UHL in both co-located and spatially separated target-masker spatial conditions using sentence recognition materials with a real-speech masker will allow for a more balanced, comprehensive, and "real-world" picture of abilities and deficits in this population.

As with any study on speech recognition, it must be noted that the stimuli used in this investigation are only one example from among an array of effectively limitless possibilities. The target and competing speech maskers were selected to simulate a commonly experienced listening scenario for students, an adult speaker with interfering child talkers. Differences in pitch and quality between the target and masker signals apparently minimized informational masking in the two-talker-babble masking conditions. Experiments that include the use of masking talkers that produce greater degrees of informational masking have been and will be useful as we try to attain a more complete understanding of children's abilities in real world listening environments. Along these lines, conditions where visual (i.e., lipreading) cues are available and head movement is encouraged might show different trends from the current results. Further, the effects of room reverberation, which tends to reduce spatial release from masking in NH listeners (Zurek et al. 2004), will be important to consider; reverberation was minimal in the sound rooms in which we tested our subjects. Plomp (1976) observed especially unfavorable effects of monaural listening in the higher reverberation conditions they studied. In addition, many studies of speech recognition, including the current one, require immediate responses to sequential unrelated sentences. It will be useful to evaluate the consequences of UHL using materials that require comprehension of stimuli that involve more sustained attention, such as paragraph-length passages (e.g., Lewis et al. 2015).

It is clear from the current study that despite having 1 ear with NH, many children with UHL, irrespective of age, sex, or degree of hearing loss, demonstrate speech-in-noise deficits across numerous listening conditions and report significantly decreased hearing-related QoL compared to age-matched peers with bilateral NH. While some of the deficits were readily predictable from the hearing losses, others were not. In the current study, there was

considerable variability in SRTs across subjects and across listening conditions, but on average subjects with unaided UHL required 3 dB higher SNRs (and up to 15 dB in individual cases) to achieve the same level of performance as NH peers. Findings continue to support the need for remote microphone technology in this population to improve the SNR in challenging listening environments. The benefit of other audiological management approaches (e.g., traditional hearing aid, bone-anchored hearing device, CROS aid, cochlear implant) requires further study. Future research is critically needed to systematically define the acute and long-term outcomes of all available audiological treatment options for children with UHL. Although not every child with UHL will be identified with developmental, socioemotional, or academic difficulties, the findings of the current study suggest that many children will experience substantial difficulties understanding speech in complex listening environments and report decreased quality of life. These findings continue to challenge the notion that hearing in 1 ear is “good enough” and suggest the need for increased audiological support in this population.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

SRTs (dB) obtained in Quiet (A), in the presence of SSN (B,D), and in the presence of TTB (C,E,F) for target-masker spatial configurations Front/Front (second row), Front/Side (third row), and Front/Right and Left (fourth row) are plotted as a function of age (in years) for all normal-hearing children (unfilled circles). Average adult data (± 1 SD) are shown as solid black squares at age 23 (mean age of adult subjects); note break in x-axis between child and adult data. The regression line represents a simple linear fit of the individual pediatric data.

*Note lower numbers indicate better performance. Additionally, the y-axis scale is different in the Quiet figure to accommodate the wider range of data.

Fig. 2.

Best-fit lines (A) and normalized best-fit lines (B) plotted as a function of age for all noise conditions. In panel C, the amount of improvement in SRT (in dB) with masker type TTB compared to SSN (difference between best-fit lines) is plotted as function of age (years) for target-masker spatial configurations: Front/Right & Left and Front/Side. In panel D, SRM (in dB) is plotted as a function of age (years) for all spatial listening conditions.

Fig. 3.

SRTs (dB) obtained in Quiet (A), in the presence of SSN (B,D,F), and in the presence of TTB (C,E,G,H) for target-masker spatial configurations Front/Normal (second row), Front/Impaired (third row), Front/Normal (fourth row) and Front/Impaired and Normal (fifth row) are plotted as a function of age (in years) for subjects with unaided UHL (unfilled circles), who wore a traditional hearing aid (H1–4) and who wore a CROS aid (C1–4). Dashed lines indicate the 10th and 90th percentiles for subjects with normal hearing. *Note lower numbers indicate better performance. Additionally, the y-axis scale is different in the Quiet figure to accommodate the wider range of data.

Fig. 4.

Percentage of subjects with SRTs in the bottom 10th percentile of subjects with NH across all listening conditions for those with normal-hearing (grey bars) and unaided UHL (black bars). ** $p < 0.01$; *** $p < 0.001$, ns= not significant

Fig. 5.

SRT deviations (number of dB from age-matched NH reference lines) as a function of degree of UHL (4-frequency PTA .5, 1, 2, 4 kHz) for all listening conditions for subjects with unaided UHL (unfilled circles), who wore a traditional hearing aid (H1-4) and who wore a CROS aid (C1-4). The regression line in each panel represents a simple linear fit to data only from subjects with unaided UHL. Note: y-axis scale is different in the Quiet figure to accommodate the wider range of data.

Fig. 6.

Box plots indicate the range of performance on the HEAR-QL-26 for each subscale as well as the total score for subject groups, normal hearing (grey box plot) and unaided UHL (white box plot). The box depicts the interquartile range transected by the median; tails extend to all, but outlier data. The mean is additionally displayed by the + symbol. Individual subject data are also overlaid on the box plots, which are staggered horizontally for visibility, for subjects with NH (unfilled circles), unaided UHL (unfilled triangles), and those using traditional hearing aids (red H1, H2, H4) and CROS hearing aid systems (blue C1–C4). For reference, the mean data obtained by Umansky, et al. (2011) are additionally displayed by the U character.

Table 1.

Demographic, Audiological, and Medical Characteristics for Subjects with UHL.

Subject ID	Testing Site	Age (yrs)	Sex	Side	PTA	Unaided SII at 65 dB SPL	Type	Onset	Etiology	Other Relevant Medical Diagnosis	EI Services	IEP	504 Plan	Academic Concerns	Remote Microphone HAT Use	Hearing Device	Device Use (mo)	Duration of HL Prior to Fit (mo)
U1	Worcester	8	F	R	50	25	S	A	Unknown	—	—	—	—	No	Yes	—	—	—
U2	Worcester	6	M	L	114	0	S	ANSD	VIII Nerve Aplasia	PDD-NOS; Social Anxiety	Yes	Yes	—	No	Yes	—	—	—
U3	Worcester	9	F	L	26	73	S	C	Connexin 26	—	Yes	Yes	—	Yes	Yes	—	—	—
U4	Worcester	10	M	L	26	80	S	A	Unknown	ADHD	—	Yes	—	Yes	No	—	—	—
U5	Waltham	8	M	R	75	0	MIX	ANSD	VIII Nerve Hypoplasia	—	Yes	—	Yes	No	Yes	—	—	—
U6	Waltham	7	F	R	46	41	S	A	Unknown	—	—	—	—	No	Yes	—	—	—
U7	Waltham	11	F	L	19	77	S	A	Unknown	—	—	—	—	No	No	—	—	—
U8	Waltham	8	M	R	119	0	S	ANSD	VIII Nerve Aplasia	—	Yes	Yes	—	Yes	Yes	—	—	—
U9	Waltham	9	M	R	119	0	MIX	A	Unknown	ADD	—	—	Yes	No	No	—	—	—
U10	Waltham	9	F	L	18	83	S	C	Unknown	—	—	—	Yes	No	Yes	—	—	—
U11	Waltham	9	M	R	124	0	S	C	Hemifacial Microsomia	—	—	Yes	—	No	Yes	—	—	—
U12	Waltham	9	M	L	23	81	S	A	Unknown	—	—	—	—	No	Yes	—	—	—
U13	Waltham	11	F	R	51	29	S	A	Viral	—	—	—	Yes	No	No	—	—	—
U14	Waltham	11	M	L	68	0	MIX	C	Abnormal Inner Ear Anatomy	—	—	—	—	No	No	—	—	—
U15	Waltham	7	F	L	95	0	MIX	A	Unknown	—	—	—	—	No	No	—	—	—
U16	Waltham	7	F	R	58	29	S	C	Unknown	—	—	—	—	No	No	—	—	—
U17	Waltham	10	M	R	119	0	S	C	Abnormal Inner Ear Anatomy	ADHD; Dyslexia	Yes	—	Yes	No	No	—	—	—
U18	Waltham	8	M	R	21	79	S	C	Unknown	—	Yes	—	Yes	Yes	Yes	—	—	—
U19	Waltham	10	M	R	46	37	S	C	Unknown	ADHD; Anxiety	Yes	—	Yes	Yes	Yes	—	—	—
U20	Waltham	9	M	R	23	85	S	A	Unknown	—	Yes	Yes	—	No	No	—	—	—
U21	Waltham	9	F	L	59	24	S	C	Unknown	—	Yes	Yes	—	No	Yes	—	—	—
U22	Waltham	10	F	L	119	0	S	C	Unknown	—	—	Yes	—	No	Yes	—	—	—
U23	Waltham	6	M	L	84	0	S	C	CMV	—	Yes	—	—	No	No	—	—	—

Subject ID	Testing Site	Age (yrs)	Sex	Side	PTA	SPL	Type	Onset	Etiology	Other Relevant Medical Diagnosis	EI Services	IEP	504 Plan	Academic Concerns	Remote Microphone HAT Use	Hearing Device	Device Use (mo)	Duration of HL Prior to Fit (mo)
U24	Waltham	11	M	L	30	68	S	C	Abnormal Inner Ear Anatomy	–	–	Yes	–	No	Yes	–	–	–
U25	Waltham	6	M	R	115	0	S	C	Abnormal Inner Ear Anatomy	–	Yes	Yes	–	No	No	–	–	–
U26	Waltham	6	M	L	60	8	S	C	Unknown	–	Yes	–	–	No	No	–	–	–
U27	Waltham	9	F	L	75	0	S	C	VIII Nerve Hypoplasia	–	Yes	–	–	Yes	Yes	–	–	–
U28	Waltham	11	F	L	80	0	S	C	Unknown	–	–	–	Yes	No	No	–	–	–
U29	Waltham	9	F	R	119	0	S	A	Unknown	–	–	Yes	–	No	Yes	–	–	–
U30	Waltham	9	M	L	44	51	S	A	EVA	–	–	–	–	No	No	–	–	–
U31	Waltham	9	M	R	6	88	S	A	Unknown	–	Yes	Yes	–	Yes	No	–	–	–
U32	Waltham	6	F	L	110	0	S	C	Unknown	–	–	–	–	No	No	–	–	–
U33	Waltham	7	M	L	113	0	S	C	Waardenburg Syndrome	–	–	–	–	No	No	–	–	–
C1	Worcester	11	F	R	81	4	S	A	EVA	–	–	–	Yes	Yes	No	CROS	11	89
C2	Waltham	12	F	R	91	0	S	C	Abnormal Inner Ear Anatomy	–	–	–	–	No	No	CROS	36	49
C3	Waltham	9	F	L	84	0	S	C	Abnormal Inner Ear Anatomy	–	–	–	–	No	Yes	CROS	12	81
C4	Waltham	12	F	L	55	40	S	A	Unknown	–	–	–	–	No	No	CROS	12	34
H1	Worcester	9	F	L	58	6	S	C	EVA	–	Yes	Yes	–	No	No	HA	3	101
H2	Waltham	7	F	L	38	54	S	A	EVA	–	–	–	–	Yes	Yes	HA	34	9
H3	Waltham	6	M	R	46	44	S	C	Unknown	–	Yes	Yes	–	Yes	Yes	HA	36	30
H4	Waltham	8	M	L	56	3	S	C	Unknown	ADHD	Yes	Yes	Yes	Yes	Yes	HA	22	76

A, acquired; ADD, attention-deficit disorder; ADHD, attention-deficit/hyperactivity disorder; ANSD, auditory neuropathy spectrum disorder; C, congenital; CMV, cytomegalovirus; CROS, Contralateral Routing of Signal; EI, Early Intervention; EVA, enlarged vestibular aqueduct; F, female; HA, hearing aid; HAT, hearing assistance technology; HL, hearing loss; IEP, Individualized Education Program; L, left; M, male; MIX, mixed; PDD-NOS, pervasive developmental disorder – not otherwise specified; PTA, 4-frequency pure-tone average; R, right; S, sensorineural; SPL, speech intelligibility index

Table 2.

Number of HINT-C Lists Presented for Each Listening Condition.

Masker Type	Spatial Configuration of Target/Masker			
	Co-located	Asymmetric		Symmetric
	Front/Front	Front/Right <i>or</i> Impaired	Front/Left <i>or</i> Normal	Front/Right & Left <i>or</i> Impaired & Normal
TTB	2	2	2	2
SSN	2	2	2	-
None (quiet)	1	-	-	-

SSN, speech-spectrum noise; TTB, 2-talker child babble

Table 3.

Slope (dB/year), Intercept, and Associated Correlation Values for all Listening Conditions for NH Child Subjects.

	Co-located <i>Front/Front</i>		Asymmetric <i>Front/Side</i> ¹		Symmetric <i>Front/Right & Left</i>	
	Quiet	TTB ²	SSN ³	TTB	SSN	TTB
Slope	−1.22	−0.78	−0.36	−0.83	−0.60	−0.43
Intercept	26.13	2.44	1.76	−2.16	−0.61	−3.07
r	0.60 ^{***}	0.75 ^{***}	0.51 ^{**}	0.67 ^{***}	0.71 ^{***}	0.36 [*]

¹ Front/Side represents averaged data from Front/Right and Front/Left,

² TTB, 2-talker child babble,

³ SSN, speech-spectrum noise,

*
p < 0.05;

**
p < 0.005;

p < 0.001

Table 4.

Mean (SD) SRM values in dB for children and adults with NH.

	Front/Side		Front/Right & Left
	<i>TTB</i>	<i>SSN</i>	<i>TTB</i>
Children	5.11 (1.46)	4.67 (1.47)	2.21 (2.12)
Adults	5.17 (2.46)	5.52 (1.29)	2.02 (2.21)
<i>p</i>-value	0.91	0.03	0.74

SSN, speech-spectrum noise; TTB, 2-talker child babble

Table 5.

Average deficit in dB relative to the NH reference for 33 subjects with unaided UHL. P- values reflect the significance of the difference between average SRT of UHL subjects versus NH reference.

	Front/Front			Front/Impaired		Front/Normal		Front/Impaired & Normal
	<i>Quiet</i>	<i>TTB</i>	<i>SSN</i>	<i>TTB</i>	<i>SSN</i>	<i>TTB</i>	<i>SSN</i>	<i>TTB</i>
Average	3.56 ***	1.84 ***	0.78 *	2.16 ***	1.68 ***	6.97 ***	5.91 ***	3.58 ***
SD	4.90	1.94	1.53	1.88	2.00	3.13	2.99	2.09

SSN, speech-spectrum noise; TTB, 2-talker child babble;

p < 0.001

*
p < 0.05

Table 6.

Mean (SD) SRM values in dB for unaided UHL subjects as well as individual SRM values for the 8 subjects with aided UHL. Data for NH subjects are repeated from Table 4. P- values reflect the significance of the difference in SRM for UHL subjects versus NH subjects.

	Front/Impaired		Front/Normal		Front/Impaired & Normal
	<i>TTB</i>	<i>SSN</i>	<i>TTB</i>	<i>SSN</i>	<i>TTB</i>
Mean NH	5.11 (1.46)	4.67 (1.47)	5.11 (1.46)	4.67 (1.47)	2.21 (2.12)
Mean Unaided UHL	4.77 (1.98)	3.67 (1.78)	−0.04 (2.89)	−0.55 (2.81)	0.60 (1.80)
<i>p</i>-value	0.42	0.01	<0.001	<0.001	0.001
H1	7.29	4.86	1.57	1.43	1.71
H2	6.43	3.00	−2.14	−2.71	0.14
H3	0.86	3.00	2.00	1.29	1.86
H4	1.43	3.29	−1.57	−0.28	−1.28
C1	1.57	−0.57	4.86	2.00	0.29
C2	−0.14	2.57	−7.00	−3.00	−4.43
C3	0.57	−1.14	−1.14	−2.71	−0.29
C4	2.57	5.00	1.14	2.86	−0.29

SSN, speech-spectrum noise; TTB, 2-talker child babble