Research Article

Auditory Comprehension in School-Aged Children With Normal Hearing and With Unilateral Hearing Loss

Amanda M. Griffin,^{a,b} Sarah F. Poissant,^c and Richard L. Freyman^c

Purpose: The purpose of this study was to measure auditory comprehension performance in school-aged children with unilateral hearing loss (UHL) and with normal hearing (NH) in quiet and in the presence of child-produced two-talker babble (TTB).

Method: Listeners were school-aged children (7–12 years) with permanent UHL ($n = 25$) or NH ($n = 14$). Comprehension of three short stories taken from the Test of Narrative Language (Gillam & Pearson, 2004) was measured in quiet and in the presence of TTB at two signal-to-noise ratios (SNRs): (a) +6 dB and (b) the individualized SNR required to achieve 50% sentence understanding in the presence of the same TTB masker in a prior study (Griffin, Poissant, & Freyman, 2019). Target/masker spatial configuration was $0^\circ/\pm 60^\circ$ azimuth.

Results: As a group, subjects with UHL demonstrated auditory comprehension abilities in favorable listening environments (i.e., quiet, +6 dB SNR) that were statistically equivalent to the NH group. However, in the most challenging listening condition (individualized SNR), many subjects with UHL demonstrated poorer comprehension performance than their age-matched peers with NH. Comprehension abilities were not associated with degree of UHL, unaided speech intelligibility index at 65 dB SPL in the impaired ear, side of UHL, or sex.

Conclusions: As a group, children with UHL demonstrated deficits in auditory comprehension compared to age-matched peers with NH in challenging listening environments. Findings highlight the importance of ensuring good SNRs for children with UHL.

It is becoming more evident that children with unilateral hearing loss (UHL) are at risk for academic underachievement, behavioral problems, psychosocial issues, and speech and language delays (Bess & Tharpe, 1984; Bess, Tharpe, & Gibler, 1986; Borg et al., 2002; Bovo et al., 1988; Culbertson & Gilbert, 1986; Davis, Shepard, Stelmachowicz, & Gorga, 1981; Fischer & Lieu, 2014; Hartvig Jensen, Børre, & Johansen, 1989; Kiese-Himmel, 2002; Lieu, 2013; Lieu,

Tye-Murray, Karzon, & Piccirillo, 2010; Martínez-Cruz, Poblano, & Conde-Reyes, 2009; Most, 2004; Oyler, Oyler, & Matkin, 1988; Peckham & Sheridan, 1976; Sedey, Carpenter, & Stredler-Brown, 2002; Young et al., 1997). However, serious questions remain about the best way to reduce the prevalence and impact of these issues in children with UHL. Although studies on academic, behavioral, and language outcomes in this population have been plentiful, fewer studies have focused on identifying the specific auditory deficits experienced in the pediatric population, which is a necessary first step to inform intervention strategies.

The limited number of speech perception studies conducted in children with UHL have revealed that these children have poorer and more variable performance than demonstrated by their peers with normal hearing (NH) even in the most favorable listening conditions (Bess et al., 1986; Bovo et al., 1988; Reeder, Cadieux, & Firszt, 2015; Ruscetta, Arjmand, & Pratt, 2005). Studies have typically measured subjects' speech perception using whole-word stimuli in the presence of noise maskers (e.g., Bess et al., 1986; Bovo et al., 1988). Only a few studies have investigated abilities using sentence-level stimuli and/or real speech masking (Corbin, Buss, & Leibold, 2017; Griffin, Poissant,

^aDepartment of Otolaryngology and Communication Enhancement, Boston Children's Hospital, MA

^bDepartment of Otology and Laryngology, Harvard Medical School, Boston, MA

^cDepartment of Communication Disorders, University of Massachusetts Amherst

Correspondence to Amanda M. Griffin:
amanda.griffin@childrens.harvard.edu

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& Freyman, 2019; Reeder et al., 2015). To the authors' knowledge, only one study (Lewis, Valente, & Spalding, 2015) has attempted to understand how UHL affects children's higher-order comprehension skills. This leaves questions about their abilities in more challenging and realistic listening environments, such as in a classroom.

Unlike the ideal listening environment found in audiology clinics, real-world spaces are more complex, replete with competing signals. Primary school classrooms are no exception. Picard and Bradley (2001) reviewed published ambient noise levels in preschool through higher education classrooms and their potential effects on speech intelligibility. Reported noise levels in traditional occupied classrooms ranged from 41.9 dBA in a junior high classroom to 75 dBA in a kindergarten classroom. Noise levels generally decreased as grade level increased. Typical signal-to-noise ratios (SNRs; i.e., the relative strength of the teacher's voice compared to the background noise in the classroom) in typical classrooms were estimated to range between +3 and +9.5 dB in second grade through junior high. Picard and Bradley (2001, p. 227) also suggest that these values may have been overestimated. The estimated SNRs are also considerably poorer than the minimum SNR of +15 dB recommended in the American Speech-Language-Hearing Association's position statement on acoustics in educational settings (American Speech-Language-Hearing Association, 2005).

To succeed academically, children must be able to comprehend orally presented information within these adverse acoustical environments. Auditory comprehension, the most complex skill described within the hierarchy of auditory abilities (Erber, 1982), is a multifaceted process that includes recall, reasoning, and making inferences. It requires not only excellent basic auditory function (e.g., detection, discrimination, and recognition) but also additional cognitive processes. Wolvin (2009) describes intrinsic factors, such as sensory processing (e.g., hearing), attention span, grammatical and lexical knowledge, working memory, cognition, past experiences, and mental and physical state, as noteworthy elements affecting a child's comprehension abilities. Extrinsic factors also affect comprehension, such as stimuli characteristics, message complexity, and, especially relevant to the current study, the acoustical environment.

It has been estimated that U.S. children spend, on average, 65% of their day engaged in listening activities (Palmer, 1997), yet studies examining speech understanding during realistic learning activities in typical classroom conditions (i.e., those that rely on auditory comprehension) are limited (Klatte, Lachmann, & Meis, 2010; Klatte, Meis, Sukowski, & Schick, 2007; Neuman, Wroblewski, Hajicek, & Rubinstein, 2010). There is recent evidence, however, that complex listening environments (e.g., noisy reverberant spaces) may affect higher-order cognitive functions involved in comprehension (Gordon, Daneman, & Schneider, 2009; Klatte et al., 2007). The theoretical premise is that the effort required to decode a speech signal in unfavorable listening environments may leave fewer resources for other cognitive duties, such as short-term memory and comprehension (Klatte, Hellbrück, Seidel, & Leistner, 2010; Picard & Bradley,

2001). Klatte, Lachmann, and Meis (2010) examined word recognition and listening comprehension in 257 children with NH aged 6–10 years, while varying masker type (background speech or classroom noise without speech) and reverberation time (RT; 0.47 or 1.1 s). On a picture-pointing word recognition task, children performed more poorly when listening in the presence of classroom noise that did not include speech interference (e.g., moving chairs, scraping feet, coughing, rustling papers) than in background speech (one female talker). Conversely, on the comprehension task as measured by a subject's execution of complex oral instructions (e.g., "Put a cross under the book that lies next to the chair."), children performed more poorly when listening in the presence of background speech than environmental classroom noise, and younger children performed more poorly than older children. The researchers speculated that the speech masker interfered with children's short-term memory required for the more complex comprehension task.

Valente, Plevinsky, Franco, Heinrichs-Graham, and Lewis (2012) assessed sentence recognition and comprehension abilities in 50 children with NH aged 8–12 years in a simulated classroom acoustic environment. Participants listened to either lecture or discussion-like material in the presence of background noise simulating indoor noise generated by heating, ventilation, and air conditioning systems, while SNR (+10 or +7 dB) and RT (0.6 or 1.5 s) varied. They found that sentence recognition scores for all subjects remained greater than 95% correct in all listening conditions. However, with similar levels of background noise and reverberation, performance was degraded on comprehension tasks, an effect more pronounced for the youngest subjects.

Lewis et al. (2015) employed the same experimental procedures and maskers as Valente et al. (2012) to evaluate comprehension abilities in children with hearing loss when listening to discussion-like material in the presence of background noise. Subjects included 18 children aged 8–12 years with either UHL ($n = 8$) or mild bilateral hearing loss ($n = 10$). At a +10 dB SNR and an RT of 0.6 s, almost all subjects performed very well on a basic sentence recognition task, with all but two subjects scoring $\geq 89\%$ correct. However, on the more challenging comprehension task, subjects with hearing loss performed more poorly and variably than those with NH. Results such as these support the notion that basic auditory tasks such as word and sentence recognition as measured routinely in the audiology clinic, even in the presence of noise or reverberation, may underestimate the deleterious effects of poor classroom acoustics on daily auditory comprehension and learning activities in children with hearing loss.

In the current project, we tested a larger group of children with UHL under listening conditions similar to those experienced in a classroom setting. Subjects were tasked to listen to short stories and answer a set of comprehension questions, a routine listening task for school-aged children. Auditory comprehension abilities were evaluated in the presence of child-generated speech masking at varying SNRs; results were compared to age-matched peers with NH. On the basis of the previous findings of Lewis et al. (2015),

we hypothesized that comprehension scores in children with UHL would be more negatively affected by speech masking than those in children with NH.

Method

This study was approved by the institutional review boards at the University of Massachusetts Amherst and Boston Children's Hospital.

Subjects

All children ($n = 76$, aged 6–12 years) who were subjects in the sentence recognition study reported in Griffin et al. (2019) participated in the current comprehension task later in the same 2-hr experimental test session. Forty-one of these children had UHL and 35 had NH. As reported in the earlier article, the large majority (all but eight) of the children with UHL recruited for the study did not wear personal hearing devices. This report of the comprehension study focuses exclusively on these unaided children.

The data analyzed in the comprehension study reported here were from a subset of the remaining 68 children (unaided UHL or NH). After exclusions, the final data set consisted of 14 children with NH and 25 children with unaided UHL. The bases of the additional exclusions were as follows: First, all 6-year-old subjects were excluded, five with NH and five with UHL. The reason was that performance fell off precipitously and was more variable below 7 years of age, whereas there were more modest or nonexistent effects of age in the 7- to 12-year-old range. Although the Test of Narrative Language (TNL; Gillam & Pearson, 2004) used here to assess comprehension is standardized for children as young as 5 years of age, the standard administration is in quiet, and children look at picture cues during several of the subtests. Our test was administered in the presence of background speech babble, and no picture cues were provided, which may explain why the test did not appear appropriate for 6-year-old children. Second, data from three of the subjects from the UHL 7- to 12-year-old group were lost due to technical errors during the running of the study. The third and largest exclusion ($n = 16$ from the NH group) was due to an initial attempt to partially counterbalance the assignment of comprehension materials ("stories") to different test conditions and test orders. It became clear after running the listeners with NH that the differences in the stories themselves and/or the questions asked about them added a substantial source of variability independent of listening condition. This difference in story difficulty would have severely reduced statistical power for the main question of group differences had we continued with the counterbalancing for the children with UHL. Because we suspended the counterbalancing, no children with UHL were excluded on this basis. Thus, all of the 25 children with UHL who otherwise qualified (7–12 years old, unaided, no technical errors) listened to the conditions in the same order and with the same story-to-condition assignment. All 14 children with NH completed the study in this same way as well. While

not part of the main data set, the results from the 16 subjects with NH who were excluded due to the counterbalancing are considered further in the Discussion section.

Subjects who met all criteria were native English speakers ranging in age from 7;0 to 12;7 (years;months). As mentioned above, 25 were children with unaided UHL (11 girls), and 14 were children with NH bilaterally (seven girls). Participants with NH were recruited from the greater Amherst, Massachusetts area. Children with UHL were recruited from the patient populations at Boston Children's Hospital, Boston, MA, and UMass Memorial Medical Center, Worcester, MA. All subjects received a comprehensive audiological assessment to confirm hearing status before participation in the study. NH was defined as hearing thresholds ≤ 15 dB HL from 250 to 8000 Hz bilaterally. UHL was defined generally following the guidelines set forth by the National Workshop on Mild and Unilateral Hearing Loss (2005): NH in one ear, defined as the average of air conduction (AC) thresholds from 250 to 8000 Hz ≤ 15 dB HL, and with hearing loss in the other ear, defined as a pure-tone average of AC thresholds at 500, 1000, and 2000 Hz ≥ 20 dB HL or AC thresholds > 25 dB HL at two or more frequencies above 2000 Hz in the affected ear. Among the 25 children with UHL (see Table 1), 21 losses were sensorineural and four were mixed. Fifteen hearing losses were congenital, whereas 10 were acquired. There were nearly equal numbers of left-sided ($n = 13$) and right-sided ($n = 12$) hearing losses. Degree of hearing loss ranged from slight to profound, with an average four-frequency pure-tone average (0.5, 1, 2, and 4 kHz) of 66 dB HL.

Experimental Apparatus

Subjects were tested at one of three testing sites across Massachusetts: 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. However, the same experimental hardware and software were used at all three testing sites. For a detailed description of the testing facilities and experimental equipment, the reader is referred to Griffin et al. (2019). Both acoustical and behavioral measurements reported in that study verified the effective equivalence of the different test booths. Subjects were seated in the center of a double-walled sound-treated booth and sat in a small wooden chair; seat height was measured 13 5/8 in. from the floor. Three loudspeakers (Yamaha MSP3 powered monitor speakers) were positioned 35 1/2 in. from the floor on speaker stands at a distance of 1 m from the center of the subject's head, at angles of -60° (left), 0° (front), and $+60^\circ$ (right) 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 three physical loudspeakers

Table 1. Demographic, audiological, and medical characteristics for subjects with unilateral hearing loss (UHL).

Subject ID (Griffin et al., 2019)	Age (years; months)	Sex	Side	PTA	Unaided SII at 65 dB SPL	Type	Onset	Etiology	Other relevant medical diagnoses	IEP	504 Plan	Academic concerns	SRT in Front/Impaired & Good ^a (Griffin et al., 2019)
U1	8;9	F	R	50	25	S	A	Unknown	None	No	No	No	–1
U3	9;5	F	L	26	73	S	C	Connexin 26	None	Yes	No	Yes	–4
U5	8;10	M	R	75	0	MIX	C	VIII nerve hypoplasia	None	No	Yes	No	–6
U7	11;5	F	L	19	77	S	A	Unknown	None	No	No	No	–7
U8	8;11	M	R	119	0	S	C	VIII nerve aplasia	None	Yes	No	Yes	–3
U9	9;6	M	R	119	0	MIX	A	Unknown	ADD	No	Yes	No	–7
U10	9;5	F	L	18	83	S	C	Unknown	None	No	Yes	No	–5
U11	9;9	M	R	124	0	S	C	Hemifacial microsomia	None	Yes	No	No	–1
U12	9;11	M	L	23	81	S	A	Unknown	None	No	No	No	–7
U13	11;0	F	R	51	29	S	A	Viral	None	No	Yes	No	–4
U14	11;1	M	L	68	0	MIX	C	Abnormal inner ear anatomy	None	No	No	No	–4
U15	7;1	F	L	95	0	MIX	A	Unknown	None	No	No	No	–2
U17	10;5	M	R	119	0	S	C	Abnormal inner ear anatomy	ADHD; dyslexia	No	Yes	No	–4
U18	8;9	M	R	21	79	S	C	Unknown	None	No	Yes	Yes	–4
U19	10;2	M	R	46	37	S	C	Unknown	ADHD; anxiety	No	Yes	Yes	–5
U20	9;3	M	R	23	85	S	A	Unknown	None	Yes	No	No	–4
U21	9;2	F	L	59	24	S	C	Unknown	None	Yes	No	No	–4
U22	10;8	F	L	119	0	S	C	Unknown	None	Yes	No	No	–6
U24	11;5	M	L	30	68	S	C	Abnormal inner ear anatomy	None	Yes	No	No	–5
U27	9;4	F	L	75	0	S	C	VIII nerve hypoplasia	None	No	No	Yes	–4
U28	11;1	F	L	80	0	S	C	Unknown	None	No	Yes	No	0
U29	9;1	F	R	119	0	S	A	Unknown	None	Yes	No	No	–3
U30	9;5	M	L	44	51	S	A	EVA	None	No	No	No	1
U31	9;7	M	R	6	88	S	A	Unknown	None	Yes	No	Yes	–7
U33	7;8	M	L	113	0	S	C	Waardenburg syndrome	None	No	No	No	–1
UHL M (SD)	9;8 (1)												–4 (2)
NH M (SD)	10;3 (2)												Range: –7 to 1 –8 (2) Range: –11 to –4

Note. PTA = four-frequency pure-tone average; SII = speech intelligibility index; IEP = Individualized Education Plan; F = female; R = right; S = sensorineural; A = acquired; L = left; C = congenital; M = male; MIX = mixed; ADD = attention-deficit disorder; ADHD = attention-deficit/hyperactivity disorder; EVA = enlarged vestibular aqueduct; NH = normal hearing.

^aSRT in Front/Impaired & Good refers to a subject's sentence reception threshold (SRT) previously obtained in Griffin et al. (2019), which approximates the signal-to-noise ratio needed to achieve 50% sentence understanding when listening to Hearing in Noise Test for Children sentences at 0° azimuth in the presence of spatially separated two-talker babble at +60° and –60° azimuth, which presented masking toward both their impaired and good ears—the same masker and target/masker spatial configuration used in the current study.

to the three angles was random; thus, on any given setup, Loudspeaker A, for example, could be placed at -60° , 0° , or $+60^\circ$.

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. The stimuli were retrieved from the computer's hard disk, converted into an analog signal by an external eight-channel 24-bit/96-kHz digital-to-analog converter (ESI GIGAPORT HD+), and then sent to all three of the previously described loudspeakers.

Experimental Design

Target Stimuli

Three short stories from the TNL (Gillam & Pearson, 2004), namely, (a) "McDonald's," (b) "The Shipwreck," and (c) "The Dragon," served as stimuli for the current study. The TNL has been empirically established to have high reliability and validity in assessing narrative comprehension and oral narration skills in children aged 5;0–11;1. The TNL is divided into two subtests: (a) narrative comprehension and (b) oral narration. Only stories and comprehension questions from the narrative comprehension subtest were used. This subtest measures an individual's ability to recall and understand information in stories produced by others (e.g., "What was the girl's name?"). It additionally measures the ability to make inferences about information that was not explicitly stated in stories (e.g., "What was the problem in the story?"). There were 11, 9, and 10 associated comprehension questions for Stories 1, 2, and 3, respectively. However, the number of scored items was slightly higher because some questions were worth more than 1 point. For example, in the question, "What were the children's names?" each name correctly identified was worth 1 point. Therefore, the total possible points were 15, 11, and 14 for Stories 1, 2, and 3, respectively. A percent-correct score was calculated for each story. Picture cues, which are traditionally used when administering Stories 2 and 3 in the TNL, were not used in the current study.

The stories and corresponding questions were recorded by an adult female talker (age 28 years) with a standard American English dialect in a double-walled sound-treated booth (IAC 1640). A cardioid condenser microphone (Audio-Technica AT2020) fit with a 6-in. nylon mesh microphone pop filter (Gator Essentials) was positioned approximately 6 in. from the talker's mouth. The microphone had a flat frequency response from 20 to 20000 Hz. The signal was fed to a preamplifier (PreSonus TubePRE) and then sent to an external sound card (Behringer U-Control UCA202), which was connected by USB to a personal computer (MacBook Pro). The volume unit meter on the preamplifier was visually monitored during live recordings to avoid any peak clipping. Recordings were made using Audacity audio-editing and recording software, with 16-bit resolution

at a 44100-Hz sampling rate. Each story was edited to remove any noise in between sentences using Adobe Audition. The stories were then scaled to the same overall root-mean-square amplitude using the Adobe Audition software package. It is important to note that the three recorded stories were not of equal durations; one story was significantly longer than the others. Story 1 had 155 words and a duration of 58 s, Story 2 had 190 words and a duration of 1 min 7 s, and Story 3 had 381 words and a duration of 2 min 29 s.

Intelligibility of the recorded stories and questions was verified on a group of young adults with NH. Ten listeners (nine women, $M_{\text{age}} = 22$ years, range: 21–32 years) with audiometric thresholds ≤ 20 dB HL at octave frequencies between 250 and 8000 Hz participated in verification testing of the stimuli. Subjects were undergraduate students enrolled in a course in the Department of Communication Disorders at the University of Massachusetts Amherst who received extra course credit for their participation. Subjects were seated in a double-walled sound-treated booth (IAC 1604) while they listened to and repeated back the stories (one phrase at a time) and corresponding questions (one question at a time). Stimuli were presented at 60 dBA via a loudspeaker (Realistic Minimus 7) positioned approximately 1.3 m from the subject's head at ear-level height (1.2 m high). Nearly every word of the recorded stories and questions was repeated back correctly. Across all 10 subjects, there were a total of four out of 9,490 words (949 words $\times$ 10 subjects) that were incorrectly repeated.

Masker Stimulus

Stimuli were selected to simulate a scenario where there is classroom chatter while a teacher is reading aloud to the class. The same speech masker used previously in Griffin et al. (2019) was employed in the current study. One 10-year-old girl and one 10-year-old boy were digitally recorded speaking a series of nonsense sentences. 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 pauses and equated in root-mean-square level, creating 60 s of continuous speech. The two maskers were presented with a random offset into the 60-s waveform and then immediately looped back to the beginning of the file and continued in this fashion until the story had finished.

Procedure

Stories were always presented from the front loudspeaker positioned at 0° azimuth. In noisy conditions, the maskers were presented from both side speakers positioned at $+60^\circ$ and -60° (one talker from each loudspeaker) at a constant level of 55 dBA and were always initiated 2 s before the onset of the story. The talker/loudspeaker configuration (i.e., which loudspeaker presented the boy or girl masking talker) was randomized subject to subject. Stories were presented in the following order: (a) in quiet at 55 dBA, which is within the range of normal conversational speech (Pearsons, Bennett, & Fidell, 1977); (b) at +6 dB SNR, which is near the average SNR estimated for occupied

regular classrooms (Picard & Bradley, 2001); and (c) at an individualized SNR (see Table 1), at which subjects achieved an average of 50% sentence understanding across two lists of Hearing in Noise Test for Children (HINT-C; see Griffin et al., 2019).¹

Subjects were asked to verbally answer a set of oral comprehension questions immediately following presentation of each story. Recorded questions in quiet were presented from the front loudspeaker positioned at 0° at a level of 55 dBA. The order of questions was consistent across subjects. The experimenter controlled the presentation of the questions. No time limit was imposed on the subjects' responses. If subjects were delayed in their response, the experimenter encouraged them with prompts like "what do you think?" or "take a guess." The actual question was never repeated, and the experimenter waited until the child said "I don't know" either verbally or through gesture before proceeding to the next question. The experimenter listened to the subjects' responses; points were awarded for acceptable responses as listed on the TNL score sheet. Most of the time, incorrect responses were obvious to the experimenter. For example, a subject may have given the incorrect name in response to the question "What was the girl's name?" or only partially answered a multiple-point question listing one of the three things in response to "What did Lisa order?" However, if the accuracy of a particular answer was not clear to the experimenter, a speech-language pathologist, who had experience administering the TNL, was consulted after the testing for guidance on how to score questionable responses. A percent-correct score was then calculated from the points earned for each story.

To familiarize subjects with the experimental task, subjects listened to a short story taken from the Clinical Evaluation of Language Fundamentals–Fifth Edition: Understanding Spoken Paragraphs subtest before listening to the three experimental stories. The practice story was presented from the front loudspeaker (0°) in quiet at 55 dBA. Subjects then answered two associated comprehension questions for this story. These two practice questions were correctly answered by all subjects.

Results

Auditory comprehension scores are plotted in Figure 1 as a function of age (years) for all subjects in each listening condition. Each data set (three listening conditions $\times$ two subject groups) was analyzed to identify any possible improvements in the comprehension task due to increasing age/development. The slopes and Pearson correlation

coefficients as well as *p* values for the lines of best fit (not shown in the figure) are reported in Table 2. With the exception of one analysis (+6 dB SNR for subjects with NH), all other analyses were not found to be statistically significant. Because of this and of the fact that the mean age was very similar across the two groups (123 months in the NH group, 116 months in the UHL group), we felt there was sufficient justification to collapse results across age and subsequently report on group means, also shown in Table 2.

The frequency distribution of scores across the two subject groups is shown in Figure 2 for each listening condition. Because the two groups had unequal sample sizes (14 subjects with NH vs 25 subjects with unaided UHL), the proportion of subjects obtaining a given score is represented instead of the raw count. For the quiet and +6 dB SNR conditions, the distributions from the two groups have substantial overlap and similar central tendencies. There was some overlap between groups in the individualized SNR condition as well, but there was also a clear difference in the distributions overall, with the UHL distribution shifted toward lower scores. For example, in the individualized SNR condition, only 29% of subjects with NH obtained a score lower than 75% correct, whereas 76% of the children with UHL fell in that range. Thus, although some of the children with UHL achieved comprehension scores on par with the children with NH, the overall trend was for lower comprehension performance from the UHL group.

The approach to statistical analysis was guided by what was and was not controlled for and emphasized in the study design. As indicated in the Subjects section, early results from partially counterbalancing stories with conditions revealed a difference in story difficulty that likely affected the results across conditions. In the absence of floor or ceiling effects, one should expect that presenting the stories at the individual sentence reception threshold (SRT) SNR (averaging -8 and -4 dB for NH and UHL, respectively) would be the most difficult condition, followed by +6 dB SNR and then by the quiet condition. The means displayed in Table 2 do not show these trends, especially so for children with NH. Because we were more interested in group differences than in confirming the expected differences in difficulty across SNR, the counterbalancing was suspended before the UHL data were collected. All 39 children from both groups included in the statistical analysis ran the study in the same way. The influence of story number on the results across conditions prevented a valid across-condition comparison but led to a straightforward approach to the group comparisons of interest. Three planned comparisons (one-way analyses of variance) were conducted, one for each SNR condition. A significant effect of subject group (NH vs UHL) was found on comprehension scores in the individualized SNR listening condition, $F(1, 37) = 7.7, p = .008$. No significant differences were found between subject groups for the quiet and +6 dB SNR listening conditions.

Additional analyses were performed on the comprehension scores of subjects with unaided UHL to determine whether performance for each listening condition was related

¹In Griffin et al. (2019), subjects listened to HINT-C sentences in the presence of two masker types and under a variety of target-masker spatial conditions. In one condition (Front/Impaired & Good), the sentence was presented from 0° azimuth and child-generated speech maskers were presented from +60° and -60° azimuth (toward subjects' impaired and good ears simultaneously). This is the same masker and target-masker spatial configuration employed in the current study.

Figure 1. Comprehension scores (percent correct) obtained in quiet (left panel), at +6 dB signal-to-noise ratio (SNR; middle panel), and at an individualized SNR (right panel) as a function of age (years) for subjects with normal hearing (black square) and unaided unilateral hearing loss (red “X”).

to specific patient variables: degree of hearing loss in the impaired ear (see Table 3) and unaided speech intelligibility index at 65 dB SPL in the impaired ear. No significant correlations were detected. Furthermore, no significant differences in percent-correct scores were found between males and females or subjects with right- versus left-sided hearing losses.

Discussion

Consideration of the Results

The current study investigated auditory comprehension abilities in quiet and in the presence of child-generated two-talker babble (TTB) in school-aged children with UHL and NH. Children listened to stories from the TNL in three listening conditions: (a) quiet, (b) +6 dB SNR, and (c) at an individualized SNR at which subjects correctly achieved 50% of HINT-C sentences. After listening to the stories, children answered recorded questions presented to them in quiet about what they had just heard. Stories were always presented from the front loudspeaker positioned at 0° azimuth, whereas the TTB was presented from loudspeakers positioned at -60° and +60° azimuth (one talker presented

from each loudspeaker), so as to simulate a teacher reading aloud to a classroom with classroom chatter off to both sides. Results demonstrated no statistical difference in comprehension performance between children with NH and children with UHL when the SNR was favorable (i.e., quiet and +6 dB SNR). However, significant differences were found between subjects with UHL and subjects with NH when the most challenging SNR was tested, with poorer performance observed in the group with UHL. In this last condition, subjects listened at a personalized SNR at which 50%-correct sentence understanding was achieved in the presence of the same speech masker and in the same target-masker spatial configuration (Griffin et al., 2019). That is, subjects listened at an SNR that produced equivalent sentence recognition performance (50% correct), yet discrepancies between the two subject groups were observed on the auditory comprehension task.

All subjects included in this study completed the tasks in the same order; subjects heard Story 1 in quiet, followed by Story 2 at +6 dB SNR, and then Story 3 at the individualized SNR. This was done to provide the greatest statistical power possible for the intergroup comparisons, which were the focus of this study. This also means that the data shown in Table 2 and in Figures 1 and 2 are most cleanly evaluated

Table 2. Mean and standard deviation values in percent correct for all three listening conditions for subjects with normal hearing (NH) and unilateral hearing loss (UHL).

Listening condition	Subject group	<i>M</i>	<i>SD</i>	Slope (percent change/year)	<i>r</i>	<i>p</i> value
Quiet	NH	74.8	13.9	3.7	.42	.14
	UHL	76.8	11.4	2.5	.23	.26
+6 dB SNR	NH	92.2	7.0	2.9	.65	.01
	UHL	89.1	8.7	-0.5	-.06	.77
Individualized SNR	NH	77.0	8.5	0.4	.07	.80
	UHL	68.6	9.4	-1.9	-.22	.29

Note. The slopes of the lines of best fit, Pearson correlations, and *p* values are additionally displayed to assess the effect of age on percent-correct scores. SNR = signal-to-noise ratio.

Figure 2. Horizontal mirrored histograms display the distribution of comprehension scores as a function of proportion of subjects with normal hearing (unfilled bars) and unilateral hearing loss (filled bars) obtained in quiet (left panel), at +6 dB signal-to-noise ratio (SNR; middle panel), and at an individualized SNR (right panel).

across subject groups at a particular SNR, not across SNRs where any differences in story difficulty or order of presentation could contribute. Indeed, the +6 dB SNR condition showed better performance than the quiet condition, and for children with NH, there was surprisingly little difference in performance between presentation in quiet and presentation at a poor SNR averaging -8 dB. Although not every across-condition finding was explored further, we had the opportunity to investigate why +6 dB SNR produced better results than the quiet condition, whether it occurred because the +6 dB condition was presented after the quiet condition (a practice or order effect) or whether there was a difference in difficulty between Story 1 and Story 2. Recall that a group of 16 children with NH from Griffin et al. (2019) completed the current experiment in the same order of quiet, +6 dB, and individualized SNR but were excluded from the main data set here because the condition-story assignment

was reversed; they heard Story 2 in quiet and Story 1 at +6 dB SNR. The results showed that Story 2 was easier than Story 1 even when it preceded Story 1. That is, the improved performance at +6 dB in the main data set appears to be due to the fact that Story 2, with its associated questions, was easier for the children than Story 1, not because the story was heard after practice with Story 1.

We also took the opportunity to compare this additional group of children with NH to the main data set regarding performance on the individualized SNR condition. All subjects who participated in Griffin et al. (2019), even those with NH who had Stories 1 and 2 swapped, heard the same story (Story 3) in this individualized SNR condition, always last in the order of presentation. As shown in Table 2, the average performance for the children with NH in the main data set was 77% correct for this condition, with an SD of 8.5 percentage points. Assuming normal distribution statistics and a known $SD = 8.5$ and $SE = 2.3$, there is approximately 68% confidence that the population mean represented by this sample would fall within ± 1 standard error (between 74.8% and 79.3%) and 95% confidence that the population mean falls within ± 2 standard errors (72.5%–81.6%). The mean for the additional 16 children with NH (who listened to Stories 1 and 2 in the swapped order) was 79.0%, and the mean across all 30 subjects with NH was 78.1%, well within the narrower confidence interval. Thus, the data from these additional 16 children who listened to Story 3 at their individualized SNR reinforce the finding of a significant group difference in this condition, with the difference expanding slightly from 8 to 9 percentage points when all 30 subjects with NH were included.

Table 3. Pearson product-moment correlation coefficient was computed to assess the relationship between the degree of hearing loss (four-frequency pure-tone average) and comprehension performance (percent-correct scores).

Listening condition	Slope	Intercept	r	p value
Quiet	-0.06	80.98	.23	.26
+6 dB SNR	-0.02	90.10	$-.06$	.77
Individualized SNR	-0.04	71.12	$-.22$	.29

Note. Slope (percent correct/dB), intercept (percent correct), r , and p values in all listening conditions for subjects with unilateral hearing loss are reported here. SNR = signal-to-noise ratio.

Several of the subjects with UHL in the current study had comorbid diagnoses by parent report, not an uncommon occurrence for children with hearing loss (Roush, Holcomb, Roush, & Escobar, 2004). Specifically, three of the 25 children with unaided UHL held an additional diagnosis of attention-deficit disorder, attention-deficit/hyperactivity disorder, and/or dyslexia. A diagnosis of an attention deficit disorder did not exclude subjects from participation in the research project; these children arrived to their study appointments while on their routine medications. The results with these three children (U9, U17, and U19) removed were computed to see if there were substantial changes. With these exclusions, the mean performance for the UHL group changed by -0.1 , 1.0 , and 0.6 percentage points in the quiet, $+6$ dB SNR, and individualized SNR conditions, respectively, not altering the findings for any of the three conditions. Especially with the replication of the NH results from the 16 additional subjects described above, the finding of a group difference in the individualized SNR condition appears to be robust. The fact that not all children with UHL performed poorly in that condition should also be highlighted. There is clear overlap in the distributions, with some children with UHL performing near or above the normal mean. Nevertheless, including all 30 children with NH who all ran this individualized SNR condition identically, only nine (30%) scored below 75% correct, compared to 19 (76%) of the 25 children with UHL. This indicates that the interquartile ranges barely overlapped.

Interpretation of the Results

In more traditional word or sentence recognition testing, it has been well established that children with hearing loss require more advantageous SNRs to achieve the same level of speech understanding as their age-matched peers with NH (e.g., Garadat & Litovsky, 2007; Litovsky, 2005). The size of the difference in SNR for equivalent performance varies across studies and depends a great deal on the specific stimuli and spatial conditions tested. Several studies have examined this SNR loss specifically in children with UHL. In one published study, children with severe-to-profound UHL (aged 6–14 years) were found to require a 2- to 9-dB improvement in SNR when listening to speech presented in multitalker babble to achieve comparable performance to peers with NH (Ruscetta et al., 2005). Griffin et al. (2019) corroborated this finding in children with varying degrees of UHL (aged 6–12 years), who, on average, required a 1- to 7-dB SNR advantage to achieve the same level of performance as age-matched peers with NH on a masked sentence recognition task (see Table 5 in Griffin et al., 2019). The exact SNR loss depended on the specific condition. Subjects were evaluated using a variety of target-masker spatial conditions and masker types, including the condition when the sentence was presented from the front loudspeaker at 0° azimuth, and child-generated speech maskers were presented from $+60^\circ$ and -60° azimuth (i.e., the specific target-masker configuration and masker type used in the current experiment). In this condition,

with symmetrically placed speech maskers, subjects with UHL, on average, required a 4 dB better SNR for equivalent performance in sentence recognition (Griffin et al., 2019).

The poorer-than-normal threshold SNR for sentences reported by Griffin et al. (2019) for children with UHL can be understood by considering the consequences of symmetrically placed fluctuating maskers at $\pm 60^\circ$ and target sentences at 0° . This condition simulates, at least crudely, the situation that may occur in classrooms where interfering speech originates from both sides of a child, who is attempting to attend to a teacher straight ahead. When the masker is speech, as was the case in this study, the SNR fluctuates over time in each ear. The independence of the two masker utterances leads to a fluctuation pattern that is different in each ear, and therefore, during some temporal epochs, the SNR is likely to be more favorable in the left ear and, at other times, in the right ear. Adult listeners with NH bilaterally can take advantage of the ear with the better SNR nearly optimally (Brungart & Iyer, 2012). The listener with UHL experiences the same fluctuations but would be at a disadvantage during instances when the more favorable SNR is in the impaired ear, especially if threshold hearing levels are poorer than the presentation level.

Whereas the expectation of a deficit among children with UHL in threshold SNR for sentences appears to have a straightforward explanation, as discussed above, the explanation for the comprehension deficit found in the individualized SNR condition in the current study may be more difficult to pinpoint. Here, the same symmetric masking condition was employed, and children listened at the SRT obtained in the previous study, which was, on average, 4 dB more favorable for children with UHL. Despite the fact that all children listened at the SNR at which they achieved 50% sentence recognition, the average performance of children with UHL was approximately 8 percentage points worse than the children with NH. One category of possible explanation is that some children with UHL had more difficulty maintaining the consistent effort required to attend to the longer story (Story 3 was about 90 s longer than the other stories), correctly perceive each sentence, remember what was heard, or synthesize the information sufficiently to answer the questions or combinations and interactions among the above. This explanation is in agreement with the conclusions of Lewis et al. (2015), who reported deficits in story comprehension in children with mild bilateral hearing loss and UHL under acoustic conditions that yielded no deficits in sentence repetition. These authors suggested that the effort required of subjects with hearing loss to listen to the long passages (10 min) may have left fewer resources for other cognitive duties required to understand and remember content. One difference in findings from the current study is that Lewis et al. observed deficits in comprehension at a positive SNR of $+10$ dB, whereas the current results showed no statistical group difference at an SNR in the same vicinity ($+6$ dB). The difference could well be related to the task used to assess comprehension in the two studies. Lewis et al. made a more extensive effort to simulate a realistic scenario, which

included use of visual cues, reverberation, and moving signal locations.

Perhaps the most important difference between the current study and that of Lewis et al. (2015) is the length of the passages used to assess comprehension, which were approximately 7.5–8 min shorter than those used in the Lewis et al. study. Had the current study employed longer passages like those in the earlier study it is possible that differences between subject groups may have been larger and/or more prevalent (e.g., observed in the +6 dB condition as well) than what was found. Future studies are warranted to clearly define how the length of listening time affects comprehension performance, a critical factor to understand given that children spend 65% of their school day engaged in listening activities (Palmer, 1997).

A second potential explanation for the current finding of a deficit in the individualized SNR condition is that listening to the adult female talker who recorded the stories presented more of a challenge for listeners with UHL than it did for the children with NH. That is, even though the groups were equated with respect to their performance on HINT-C sentence recognition in the two-talker child masker and target-masker spatial configuration, there could be acoustic features of the target talker's utterances in the current study that contributed to an unequal difficulty level between the groups. One difference, among several, that might be important is that the target talker in the HINT-C sentences is male and the talker for the story utterances was female. With maskers spoken by children in both studies, the disparity between target and masker fundamental frequency is expected to be smaller in the current study than with the male talker. The HINT-C sentence recognition data from Griffin et al. (2019) showed little evidence of a contribution from the informational type of masking, whereas it is unknown whether there was an informational masking component for any subjects in the current experiment. It could be challenging, but not impossible, to design a study in which this confound between interpretations is entirely removed. For example, if the same acoustic waveforms used in a story form were also used in a sentence recognition format, then no acoustic differences between the utterances would exist between the two tasks. Constructing and implementing such a design could be a focus of future investigation.

Implications

One of the goals of this study was to identify deficits in auditory performance that may underlie the academic underperformance reported in previous studies (e.g., Bess & Tharpe, 1984; Blair, 1985; Lieu et al., 2010). In the current study, the performance of UHL and NH groups was not statistically different in quiet and at +6 dB SNR. Evidence of reduced performance in the children with UHL appeared in the individualized SNR condition where SNRs were in the negative range. The data show that, within this range of negative SNRs, many subjects with UHL had more difficulty answering the story questions despite listening in more favorable conditions than the NH group. There were

also differences in story duration, with Story 3, always presented during the individualized SNR condition, being considerably longer than the other two. Despite this longer duration, children with NH showed no signs that this was a more difficult story, surprisingly demonstrating at least as good performance for Story 3 presented at an SNR averaging –8 dB as for Story 1 in quiet (see Table 2). While comprehension of Story 3 was significantly poorer for the children with UHL, the design of the current investigation does not allow us to rule out the potential impact of increased story length and its interaction with decreased SNR in that condition.

Another important issue to consider is what typical classroom acoustic conditions are and how they relate to the current test conditions and findings. Specifically, the amount of time that children have to cope with negative SNRs appears to be an important consideration. The literature on classroom acoustics prior to 2001 reviewed by Picard and Bradley (2001) suggests that +6 dB SNR is within the typical range, which is why it was chosen as one of the conditions here, but there is significant variability as well as uncertainty in the measurement. Noise levels in classrooms ranged from 41.9 to 75 dBA, generally decreasing as grade level increased (see Figure 1 in Picard & Bradley, 2001). Typical SNRs ranged between +3 and +9.5 dB, with extremes of –7 to +23 dB noted across the different studies (Blair, 1977; Blake & Busby, 1994; Houtgast, 1981; Markides, 1986). At the same time, the review by Picard and Bradley acknowledged the challenges in establishing central tendencies and distributions of speech and noise levels in typical classrooms. The review cites concerns about the reliance on the Lombard effect in estimating teachers' voice levels (p. 227), which is not discounted, but adds an additional source of variability and uncertainty to the estimation of SNR. Picard and Bradley also cite concerns about the overestimation of SNR more generally and infer that negative SNRs are more likely to occur in classrooms of younger students than past reports have suggested.

An additional noteworthy issue mentioned by Picard and Bradley (2001) is the increasing trend toward modes of instruction where students divide into multiple small groups and work in these multiple clusters. A continuation of that trend to the present day only increases the expectation of higher noise levels in classrooms. A more recent review of both traditional enclosed classrooms and open plan classrooms (Shield, Greenland, & Dockrell, 2010) contained 124 references, indicating significant interest in this topic. This summary suggests that overall background levels in traditional classrooms where there is group work range from 70 to 77 dBA. Significant and probably unrealistic reliance on the Lombard effect would be required to achieve consistently positive SNRs from teachers in such scenarios; on the other hand, the decreased student-to-student distance within such scenarios would presumably have some positive effects. The current finding of statistically equivalent performance between groups in comprehension for a relatively short passage at +6 dB SNR is reassuring. However, because subjects with UHL performed worse at –4 dB SNR

than children with NH did at -8 dB SNR, the current data reinforce the imperative for maintaining positive SNRs in the classroom, especially for children with UHL.

It is also possible that auditory performance in environments and contexts beyond what we were able to measure in this study is more relevant. These include rooms with reverberation (e.g., Lewis et al., 2015; Valente et al., 2012), roving target signals (e.g., Lewis et al., 2015), roving masker signals, interfering sounds that are more realistic and attention grabbing, presence of visual information (e.g., Lewis et al., 2015), academic tasks that require multitasking such as listening to orally presented materials while note-taking (e.g., McFadden & Pittman, 2008), and so forth. It is certainly the case that children with UHL deal with a broad range of environments beyond the symmetrical masking configuration used here. For example, when the target signal is in front but the masking sounds are presented solely toward the side of the NH ear, the relative deficit in sentence recognition threshold can be even greater than was found for the symmetrical masker used here (Griffin et al., 2019). Even worse scenarios unquestionably occur, such as when the signal to be attended to is toward the side of the poorer ear and interfering sounds are toward the good ear. With so many possible listening scenarios and the presumed large variation in what children experience, a causal relationship between specific auditory perceptual deficits and academic deficits may be impossible to establish for the individual child. Nevertheless, we can try to minimize the situations in which children experience unfavorable SNRs through classroom modifications and strategic seating as well as enhancing SNRs through assistive listening devices, such as remote microphone technology. Further investigation is warranted to understand if other hearing devices indicated for UHL may be of benefit.

This work reinforces the importance of evaluating higher level auditory comprehension skills when assessing a child with UHL, in addition to more traditional word or sentence recognition measures. However, corroboration of the kinds of results reported in this study and by Lewis et al. (2015) with larger samples is important as a first step. Across the two studies, 33 children with UHL were reported on. A much larger sample will be needed to achieve a better understanding of the risk of children with UHL having poor comprehension abilities while achieving adequate sentence recognition performance. The current approach to assessing auditory comprehension involved extended listening followed by questions. The importance of the duration of continuous listening in this population, and how it interacts with SNR, has not been specifically investigated to our knowledge. Other question-and-answer approaches (e.g., Best, Streeter, Roverud, Mason, & Kidd, 2016) have been explored and need to be compared to the current approach in this population as well. Identifying co-occurring risk factors and educational outcomes that correlate with performance on auditory comprehension tasks will also be important. Should the current conclusions be confirmed and expanded upon in larger scale studies, a determination of the clinical efficacy of

assessing comprehension in children with UHL might be undertaken.

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