Immediate and long-term effects of hearing loss on the speech perception of children

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The purpose of the present study was to examine the immediate and long-term effects of hearing loss on the speech perception of children. Hearing loss was simulated in normally-hearing children and their performance was compared to that of children with hearing loss (long-term effects) as well as to their own performance in quiet (immediate effects). Eleven children with normal hearing (7–10 years) were matched to five children with mild to moderate sensorineural hearing loss (8–10 years). Frequency-shaped broadband noise was used to elevate the hearing thresholds of the children with normal hearing to those of their matched hearing-impaired peer. Meaningful and nonsense sentences were presented at five levels and quantified using an audibility index (AI). Comparison of the AI functions calculated for each group and listening condition revealed a significant, immediate effect of elevated hearing thresholds in the children with normal hearing but no long-term effects of hearing loss. The results of this study suggest that hearing loss affects speech perception adversely and that amplification does not fully compensate for those effects. However, the data suggest that over the long term children may develop compensatory strategies to reduce the effects of hearing loss. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3177265]

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I. INTRODUCTION

Children's ability to perceive speech begins early in life and matures throughout adolescence (Elliott, 1979; Holt and Carney, 2007; Stelmachowicz *et al.*, 2000). The maturation of speech perception proceeds over a long period of time suggesting that it is an advanced skill. Research showing the earlier maturation of auditory skills that form the foundation for speech perception (e.g., intensity discrimination, temporal resolution, and localization) supports this notion (Buss *et al.*, 2009; Allen and Wightman, 1994; Stuart, 2005; Wightman *et al.*, 1989; Van Deun *et al.*, 2009). Additionally, the results of other studies suggest that auditory skills are reorganized periodically throughout development to form the mature, efficient, and robust perceptual processes needed to perceive speech (Boothroyd, 1997; Gershkoff-Stowe and Smith, 1997; Nittrouer and Miller, 1997).

Less is known about the development of speech perception in the presence of hearing loss (HL). Fundamental to an understanding of speech perception in children with HL is how they differ from adults with HL. Adults generally acquire HL later in life after communication skills are well established. Children do not have the same advantage. Instead, children with HL struggle to *learn* to communicate while adults struggle to *continue* to communicate. This places children at risk for delayed or impaired speech perception development. Jerger (2007) summarized well our current state of knowledge regarding the development of speech perception in children with HL and concluded that, in general, basic auditory skills develop more normally than the advanced skills necessary for linguistic processing. Also, children with more severe hearing impairment demonstrate greater perceptual difficulties than children with milder degrees of HL. Later, Jerger *et al.* (2009) provided additional evidence that children with HL process auditory stimuli differently than children with normal hearing (NH). They examined the development of phonological processing and found that the presence of HL predisposes young children to represent speech more in visual rather than in auditory forms compared to children with NH. Although these visual representations eventually take on more appropriate auditory forms, there is evidence that auditory representations may be irrevocably affected by HL in childhood and that those effects may be carried into adulthood (Pittman, 2008).

To overcome the effects of elevated hearing thresholds, amplification is routinely provided to children with HL (e.g., hearing aids) so that they may receive a signal of sufficient audibility. With amplification, few differences between groups are observed when listening in quiet (Stelmachowicz *et al.*, 2000) suggesting that speech perception is comparable at suprathreshold levels. However, significant effects of HL re-emerge when speech is presented in noise (i.e., background competitor) suggesting that elevated hearing thresholds alone do not fully account for the effects of HL. Hicks and Tharpe (2002) examined word recognition in children with NH compared to children with HL who wore their personal hearing aids. The stimuli were presented in quiet and at several signal-to-noise ratios. They found small but significant differences in performance between the groups (mean score ~85% HL and 92% NH) in the most difficult (signal-to-noise ratio +10 dB) as well as greater variability in performance (standard deviation ~10% HL and 5% NH). Although amplification was provided, the poorer performance of the children with HL suggests that factors in addition to elevated thresholds affected their performance.

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One likely factor may be the varying degrees of audibility provided by children's personal hearing aids. Scollie (2008) carefully examined speech perception in noise as a function of audibility for children with HL compared to children with NH. The purpose of her study was, in part, to determine whether or not the performance of children with HL could be predicted on the basis of the audibility of the stimuli. Transfer functions were derived for the children with NH that accounted for 94.6% of the variance in the data. Unfortunately, the same transfer function accounted for only 87% of the variance in the data for the children with HL. The results indicate that speech perception in children with HL cannot be predicted solely on the basis of age and stimulus audibility.

The results of these studies suggest that the full effect of HL is not captured by estimates of hearing threshold. This would be consistent with studies demonstrating the suprathreshold psychophysical deficits that accompany mild to moderate HL (e.g., poor frequency selectivity, poor temporal resolution, and loudness recruitment) (Fabry and Van Tasell, 1986; Humes *et al.*, 1987; Needleman and Crandell, 1995; Dubno and Schaefer, 1992, 1995; Dubno *et al.*, 2000). Suprathreshold deficits would also explain the difficulty that hearing-impaired children (and adults) experience in noise.

Another possibility is that the presence of HL may delay or impair the development of speech perception. That is, HL, which can occur at any time during childhood, may interact adversely with the development of speech perception. It can be argued that any examination of speech perception in children with HL would be confounded by the interaction between HL and the development of speech perception. However, it is likely that the effects of suprathreshold deficits and developmental factors co-occur.

The purpose of the present study was to examine the effects of elevated hearing thresholds on the speech perception of children with NH. That is, HL was simulated in children with NH so that the immediate and long-term effects of HL could be determined. Immediate effects were examined by comparing speech perception under conditions of NH and simulated HL. Long-term effects were examined by comparing the performance of children with simulated HL to that of children with actual HL. To simulate HL, hearing thresholds were elevated using a noise masker. This form of simulated HL has been used widely to examine the effects of HL in adults (Fabry and Van Tasell, 1986; Humes *et al.*, 1987; Needleman and Crandell, 1995; Dubno and Schaefer, 1992, 1995; Dubno *et al.*, 2000). It is considered to be the most valid approach to simulating sensorineural HL because the effects of masking are localized at the level of the cochlea and approximate well the frequency selectivity and loudness recruitment experienced in the impaired ear (Dubno and Schaefer, 1992; Humes *et al.*, 1988). Dubno and co-workers used noise masking successfully to examine the effects of HL in adults (Dubno and Ahlstrom, 1995; Dubno and Schaefer, 1992, 1995; Dubno *et al.*, 2000). To date, no studies of simulated sensorineural HL have been conducted in children.

A two-step approach was used. First, the speech perception of children with NH was examined in quiet and in a condition of simulated HL. The stimuli were frequency shaped relative to the children's quiet and masked thresholds to provide equivalent sensation in both listening conditions. Performance in each condition was compared to determine whether or not speech perception was significantly poorer when the hearing thresholds were elevated even though similar audibility was provided. Second, the speech perception of children with HL was measured with the same frequency-shaped stimuli presented to the children with NH in the simulated HL condition. The results were compared to determine whether or not the speech perception of children with HL is effected by factors in addition to elevated hearing thresholds. It was hypothesized that (1) speech perception would be poorer in the presence of elevated hearing thresholds and (2) children with HL would demonstrate poorer speech perception than children with simulated HL.

Finally, for both the quiet and masked listening conditions, performance measures for meaningful and nonsense sentences were obtained to capture the effects of familiar and unfamiliar communication contexts. Research has shown that the psychometric functions relating speech intelligibility to perception in young children and adults differ for materials having high- and low-predictability (Dubno *et al.*, 2000; Dirks *et al.*, 1986). That is, children require higher presentations levels for speech materials that are less familiar to them. Also, the linguistic development of children with mild to moderate HL is, on average, 2 years behind that of children with NH (Pittman *et al.*, 2005) and the delay is greater for children with more severe losses (Blamey *et al.*, 2001). It was anticipated that the effects of HL would be more apparent for nonsense sentences than for meaningful sentences. If so, the hypothesis that long-term HL negatively impacts the development of speech perception would be supported.

II. METHOD

A. Participants

Participants were 5 children with HL between the ages of 8 and 10 years with mild to moderate sensorineural HLs and 11 children with NH between the ages of 7 and 10 years. The HLs were known to be sensorineural by history, and thresholds were confirmed on the day of testing. Prior to testing, otoscopy and tympanometry were performed to confirm normal middle-ear function. Vocabulary age (VA) was determined using the Peabody Picture Vocabulary Test (PPVT), Form IIIB (Dunn and Dunn, 2006). Children with NH were matched to each child with HL based on their chronological age (CA). With the exception of two children with NH, each child was within 1 year of the CA of the child with HL. Differences in VA ranged from 1 month to 5 years, 2 months. Table I lists the gender, CA, standardized PPVT score, VA, and hearing thresholds of each child. The first three children with HL listed in the table had flat HL configurations whereas the remaining two children had sloping, high-frequency HLs.

Pure-tone thresholds [in decibel sound pressure level (SPL)] were obtained at octave frequencies from 0.25 to 8 kHz in the right ear only. The children were instructed to push a button (computer mouse, secured to a table) when

TABLE I. ID, group, gender, CA, standardized PPVT score, VA, and hearing thresholds for the children with HL and masked thresholds for the children with NH. Average minimum audibility levels for normal-hearing young adults (NHAs) are also provided.

ID	Group	Gender	CA (y:m)	PPVT Std.	VA (y:m)	Hearing thresholds (kHz) 0.25	0.5	1 (dB SPL)	2	4	8	rms error (dB)
HL1	HL	M	10:3	80	7:8	61	59	54	54	64	41	
NH1A	NH	M	7:4	107	8:0	62	58	53	58	70	38	4.3
NH1B	NH	M	10:3	103	10:10	66	56	53	50	58	36	2.4
NH1C	NH	F	10:4	113	12:6	64	61	55	55	62	37	3.3
HL2	HL	F	10:12	101	11:0	63	64	70	76	50	56	
NH2A	NH	M	10:7	94	9:8	62	68	75	71	63	56	6.3
NH2B	NH	F	10:7	106	11:6	66	62	68	79	52	55	2.3
HL3	HL	F	8:11	82	6:10	68	64	71	61	58	58	
NH3A	NH	M	8:10	121	12:00	68	64	72	61	59	59	0.7
HL4	HL	F	8:2	115	9:11	30	20	21	51	52	79	
NH4A	NH	F	7:11	107	8:7	35	29	28	51	48	83	5.6
NH4B	NH	M	8:4	108	9:4	29	27	26	54	60	79	4.9
NH4C	NH	M	10:7	100	10:2	24	22	23	48	55	79	3.2
HL5	HL	M	8:11	114	10:10	49	49	46	73	74	84	
NH5A	NH	F	8:4	116	10:6	44	49	53	70	71	86	4.0
NH5B	NH	M	9:6	108	10:9	47	50	52	59	75	91	6.9
NHAs (minimum audibility levels)						25	17	11	12	11	18	

they heard a beep. The signal duration was 1000 ms, including 20 ms rise-fall ramps. Threshold estimation was accomplished by a single interval, adaptive procedure using a stepping rule that approximated the 70.7% point on a psychometric function (Levitt, 1971). The initial step size was 20 dB until the first reversal, followed by a step size of 4 dB for 4 reversals and then 2 dB for 5 reversals. Initial signal levels were above the hearing thresholds of both the children with NH and with HL. No feedback was provided for correct or incorrect responses. The arithmetic average of the levels corresponding to the final five reversals was taken as the threshold estimate. Thresholds were repeated and averaged.

Elevated thresholds were simulated in the children with NH using a broadband noise that was generated and filtered digitally using ADOBE AUDITION (v1.5). These children will be referred to as the noise-masked NH children. The initial octave-band levels of the noise were calculated using critical ratio predictions (Hawkins and Stevens, 1950). The spectrum level of the noise was then adjusted manually (usually in 1–3 dB steps) until the masked thresholds were within ±4 dB of the target thresholds. At least two thresholds were obtained at each frequency and averaged.

Figure 1 displays the pure-tone thresholds for the five children with HL (open circles) and for the noise-masked NH children (filled circles). The thresholds of all five children with HL are shown in the lower right panel. The shaded area represents the range of thresholds obtained from 11 young adults with NH using the same equipment and procedures. The data in Fig. 1 indicate that the children with HL had mild to moderate sloping or flat HLs that were approximately 20–70 dB above normal. Also, the thresholds of the noise-masked NH children were in good agreement with the target thresholds of the children with HL. To evaluate the match

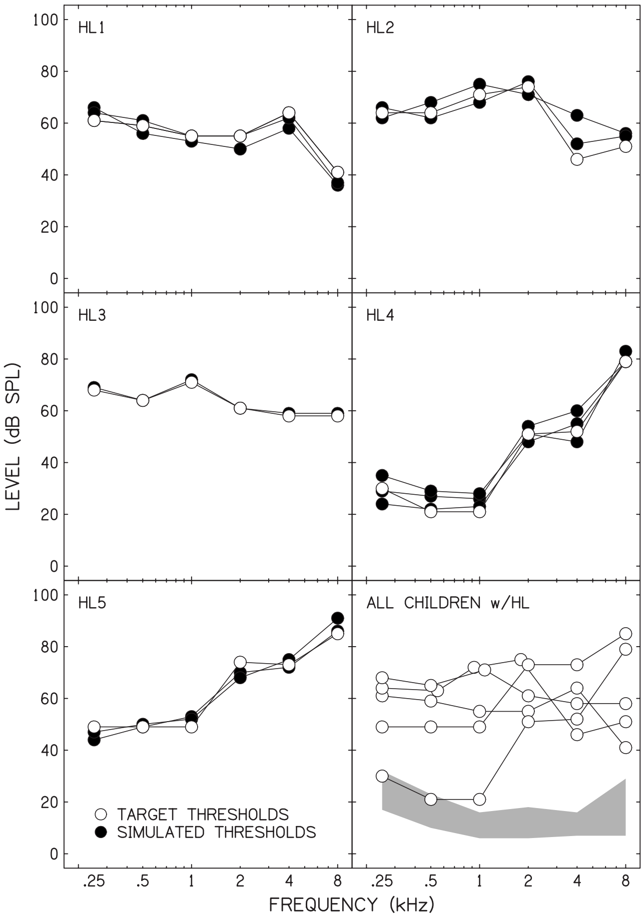

FIG. 1. Puretone thresholds for the five children with HL (open circles) and for the noise-masked NH children (filled circles). The thresholds of all five children with HL are displayed in the lower right panel. The shaded area represents the range of minimum audibility in NH adults for the equipment and procedures used.

between the target and obtained thresholds, the rms error was calculated for each noise-masked NH child. The individual rms errors varied between 0.7 and 6.9 dB indicating a close match between the target thresholds and those achieved through masking. These results are comparable to the rms error of four adults with similar HL configurations (2.2–6.1 dB) reported by Humes *et al.* (1987). The children's performance indicates that they were able to respond as reliably as adults in an abbreviated masking procedure. The thresholds obtained for the noise-masked NH children and the children with HL are provided in Table I, as well as the reference levels for NH adults.

B. Stimuli

The stimuli were two lists of meaningful sentences and two lists of nonsense sentences. Each sentence was comprised of 4 words and each list contained 30 sentences. The same words were used to construct both types of sentences. The meaningful sentences were grammatically and semantically correct (e.g., "Tough guys sound mean") whereas the nonsense sentences were grammatically correct, but semantically anomalous (e.g., "Blocks can't run sharp"). The sentences were generated originally for a study by Boothroyd and Nittrouer (1988) and then supplemented by Stelmachowicz *et al.* (2000). The sentences were rerecorded for this study using a female talker having a standard American dialect. The stimuli were digitally recorded at a sampling rate of 22.05 kHz using a microphone with a flat frequency response to 10 kHz (AKG, C535 EB). Individual sentences were extracted from the original recording, equated for rms level, and saved in separate files using ADOBE AUDITION (v1.5).

The sentences were first frequency shaped to accommodate the elevated thresholds of each child with HL and his/her noise-masked NH counterpart. DSL V5.0A fitting parameters provided approximate targets for average conversational speech (Scollie *et al.*, 2005). The targets were derived using age-appropriate real-ear-to-coupler differences and a speech weighted input level of conversational speech (65 dB SPL) and expressed in dB SPL relative to measures in a 2-cm^3 coupler. Because the stimuli were presented via supra-aural rather than insert earphones, target levels were approximated my measuring the 1/3-octave band levels developed in a 6-cm^3 coupler. The highest presentation level was 5 dB above the target levels with the 4 remaining presentation levels decreasing in 5 dB steps. These presentation levels were chosen to provide a range of sensation levels that would result in scores above floor and below ceiling values.

Figure 2 shows the hearing thresholds (filled circles) and the equivalent internal noise levels (solid line) of a child with HL in the upper panel. The middle and lower panels show the masked and quiet thresholds, respectively, for a child with NH. The solid line in the middle panel indicates the level of the masking noise used to elevate threshold. The dashed lines in each panel show the long-term average of the frequency-shaped sentences in 1/3-octave bands. Note that the sensation level of the stimuli was similar across frequency for both the child with HL and the noise-masked NH child (upper panels). Likewise, sensation level was similar for the child with NH in the masked and quiet listening conditions (lower panels). Sensation level was carefully controlled to reduce variability in performance that may result from variations in amplitude across frequency.

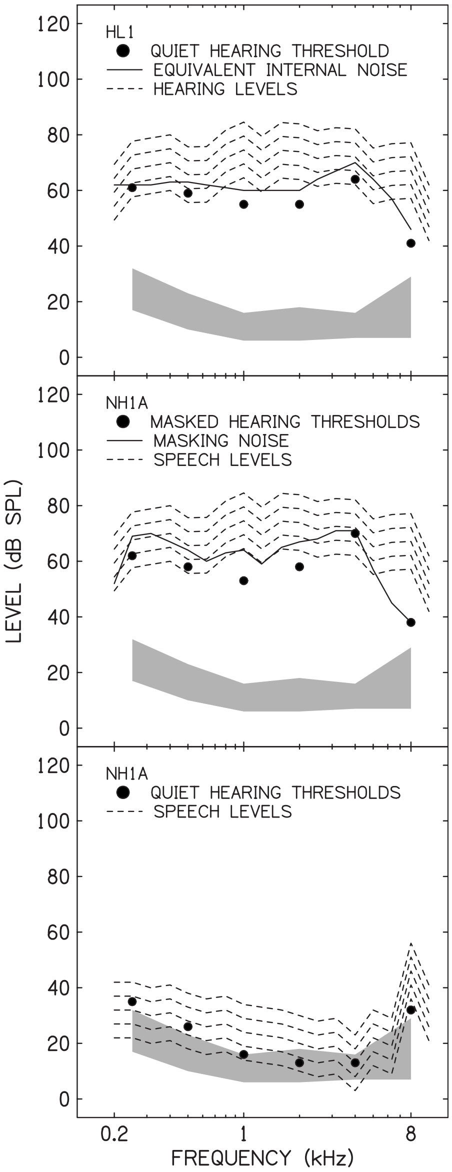

FIG. 2. Quiet pure-tone thresholds (filled circles) are shown for a child with HL in the upper panel. Masked and quiet pure-tone thresholds for a child with NH are shown in the middle and lower panels, respectively. The long-term average of the frequency-shaped sentences is shown in 1/3-octave bands at each of five presentation levels (dashed lines). The solid line represents the long-term average of the masking noise for the child with NH and the equivalent internal noise level for the child with HL. The shaded area represents the range of minimum audibility for a group of NH young adults.

Sensation levels were calculated separately for the quiet and noise listening conditions. For the quiet condition, an estimate of internal noise level was calculated for each band by subtracting the normal critical ratio (Hawkins and Stevens, 1950) from the hearing level in SPL and then adding the bandwidth (in decibel) within each 1/3-octave band to that value (Sherbecoe and Studebaker, 2002; Studebaker *et al.*, 1993). This procedure produced internal noise levels that were within 7 dB of the hearing thresholds. For the noise condition, the broadband noise used to elevate the thresholds as well as the speech stimuli were recorded in a 6-cm^3 coupler. rms amplitude was calculated in 1/3-octave bands. The ratio of speech-to-noise in each band was then determined and used to calculate the audibility of the speech stimuli.

To calculate audibility, the frequency-shaped sentences were concatenated into a single file and recorded in a 6-cm^3 coupler. Rms amplitude was measured in each of 18 1/3-octave frequency bands between 0.2 and 8 kHz using a 40 ms Hanning window with 50% overlap. To approximate the peaks of speech, 15 dB was added to the rms level in each 1/3-octave band. An audibility index (AI) was then calculated using the following formula:

$$\mathrm{AI} = \frac{1}{30}\sum_{i=1}^{18}[(\mathrm{SNR}_i + 15)W_i]\mathrm{LDF}_i,$$

where i is the number of the 1/3-octave band and SNR is the speech-to-noise ratio for the ith band. The result was multiplied by the importance value assigned to each band (W_i) and summed. As in previous studies involving these materials (Stelmachowicz *et al.*, 2000), the importance function for short passages was used (American National Standards Institute, 1997). Finally, a level distortion factor (LDF_i) was included in the calculation to accommodate for distortion that may occur at elevated presentation levels. The standard speech levels (Ui) provided in the ANSI standard were used.

C. Procedure

All testing was conducted in a sound-treated booth meeting ANSI standards for ambient noise (ANSI, 1999). All stimuli were processed using custom laboratory software designed for use with children and controlled with a standard desktop PC. The stimuli were presented monaurally under earphones having a flat frequency response through 10 kHz (Sennheiser, 25D). The laboratory equipment was calibrated prior to data collection by adjusting the overall output of the transducer for a 1 kHz pure tone in a 6-cm^3 hard-walled coupler to 125 dB SPL and then documenting the voltage at the earphone. Calibration was confirmed prior to testing each child.

For the sentence perception task, each child was instructed as follows: "You will hear a woman say a sentence. Some of the sentences will be normal and some will be silly. Listen to each sentence and repeat as much of it as you can. It's ok to guess. If you don't know, just say so." 6 sentences (24 words) were presented at each of the 5 presentation levels and 2 listening conditions (quiet and masked). The presentation levels proceeded from highest to lowest for all children. The order in which the sentence types were presented (meaningful and nonsense) was counterbalanced across children. Although the timing of the experiment was controlled by the laboratory software, the child's responses were self-paced. Specifically, after a sentence was presented, the child was allowed to respond at his/her own pace. The maximum response window was 15 s. As soon as the child responds the examiner entered the response on a computer monitor, which then prompted the presentation of the next sentence after a 1000 ms delay. The examiner entered the number of words (0–4) that the child was able to repeat correctly. The order of the words provided by the child or the addition of extra words was not considered during scoring. A second examiner was positioned outside the sound-treated room to administer the experiment and to record the child's responses in written form. The scores from the two examiners were compared and averaged. The mean difference between examiners for scores across all listening conditions (24 words) was 0.6 words with a range of 0–7 words. The median difference between examiners was 0 words.

Although the monitor microphone on the audiometer was used by the second examiner to hear the child's responses, a professional recording microphone was placed in front of the child with instructions to speak into it so that the examiner outside the booth could hear what was said. Because children typically respond well to microphones, there was little or no issue with the clarity of their speech. In the event the child's response was unclear, either examiner could request that the child repeat his/her answer. No feedback regarding the accuracy of the responses was provided.

III. RESULTS

Speech perception was examined as a function of stimulus audibility. Transfer functions were generated for each group, listening condition, and sentence type. That is, proportion correct (PC) was estimated using the following formula:

$$\mathrm{PC} = 1 - 10^{(-\mathrm{AI}+k)/\mathrm{S}},$$

where k and S are constants determined in a least-squares fit procedure for each data set. The constant k determines the vertical position of the function along the ordinate whereas the constant S is responsible for the shape of the function. Differences between the transfer functions derived for each group and listening condition were determined using a procedure described in Stelmachowicz *et al.*, 2000. In this procedure, functions that are significantly different from one another are best described by two separate functions rather than a single function for the combined data. This analysis captured the variability in performance within and across groups. The procedure requires the calculation of residuals derived from the actual data points and the performance predicted by the transfer function (see Stelmachowicz *et al.*, 2000 for a step-by-step procedure).

Figure 3 shows the performance for the children with NH as a function of AI for the quiet (open symbols) and noise-masked (filled symbols) conditions. The meaningful and nonsense sentences are shown in the upper and lower panels, respectively. The correlations between predicted and observed scores were 0.62 and 0.58 in quiet for the meaningful and nonsense sentences, respectively. Correlations for the noise-masked condition were 0.71 and 0.65 for the meaningful and nonsense sentences, respectively. The predictive accuracy of the transfer functions improved with masking noise, more for the meaningful sentences than for the nonsense sentences. These correlations are similar to those reported in Stelmachowicz *et al.*, 2000 for their NH 8- to 10-year-old children listening in quiet. However, they reported

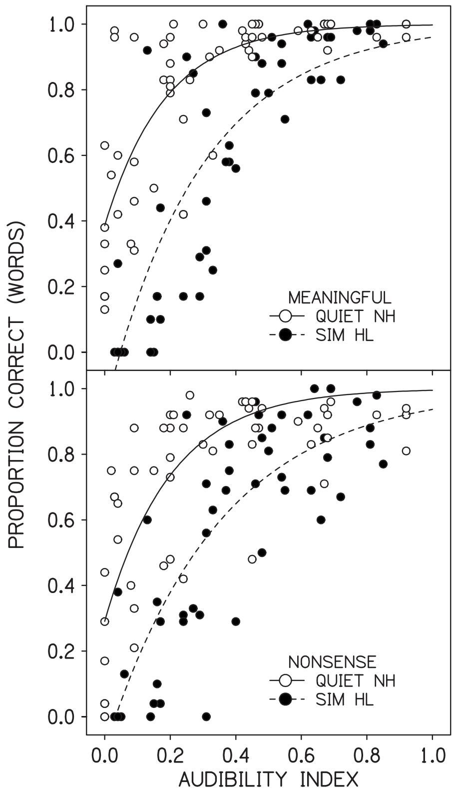

FIG. 3. Speech perception (in PC) as a function of audibility (AI) for the meaningful sentences in the upper panel and for the nonsense sentences in the lower panel. The open symbols are the data for the children with NH listening in quiet (quiet NH). The filled symbols are for the same children in the simulated HL condition (Sim HL). The dashed and solid lines are AI transfer functions for each listening condition.

higher correlations for the nonsense sentences for all but their youngest age group (5 year olds). Figure 4 shows the performance of the children with HL (open symbols) and the noise-masked NH children (filled symbols). The meaningful and nonsense sentences are shown in the upper and lower panels, respectively. Correlations between predicted and observed scores for the children with HL were similar to those of the noise-masked NH children for the meaningful and nonsense sentences (0.65 and 0.67, respectively).

For comparison, the transfer functions for each group and condition are shown together in Fig. 5. The immediate effects of HL on the perception of speech were determined by comparing the performance of the children with NH in quiet (quiet NH) to that of the children with simulated hearing loss (Sim HL). No significant difference was found for the meaningful sentences [$F(81,79)=1.2598$, $p=0.1522$]; however, a significant difference was observed for the nonsense sentences [$F(92,90)=2.0753$, $p=0.0003$]. That means that similar variability in performance was observed in both listening conditions for the meaningful sentences whereas performance for the nonsense sentences was better described by two separate transfer functions. These results indicate that the immediate effects of HL are more apparent for unfamiliar materials than for familiar ones. Because the development of speech perception is a process of decoding unfamiliar utterances, these results suggest that HL may significantly impede that development.

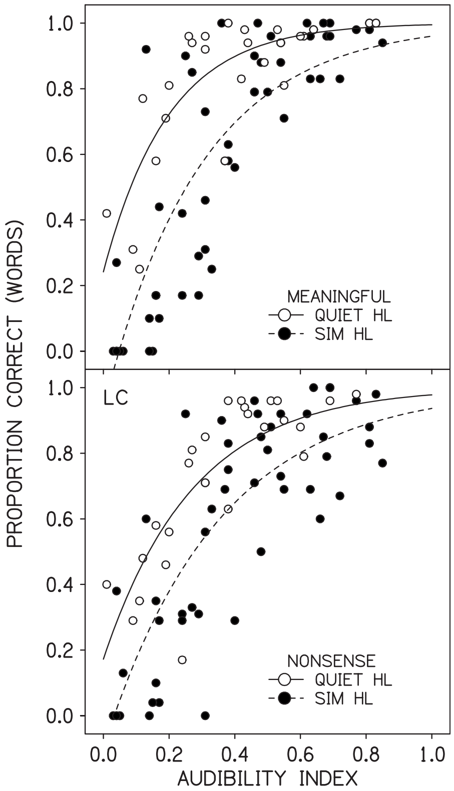

FIG. 4. Same convention as in Fig. 3 but the open symbols are the data for the children with HL (quiet HL) and the filled symbols are for the children with NH in the simulated HL condition (Sim HL). The dashed and solid lines are AI transfer functions for each group.

The long-term effects of HL on the perception of speech were determined by comparing the performance of the children with HL (quiet HL) to that of the noise-masked NH children (Sim HL). No significant difference was observed for the meaningful [$F(59,57)=1.3756$, $p=0.1144$] or nonsense sentences [$F(64,62)=1.1832$, $p=0.2537$]. It is interesting to note that the performance of the children with HL fell in between that of the NH children in the quiet and simulated HL conditions. In a final analysis, the performance of the children with HL (quiet HL) was compared to that of the children with NH in the quiet listening condition (quiet NH) for the nonsense sentences only. The nonsense sentences were chosen because a significant difference was observed between listening conditions for the children with NH. No significant difference was observed between the children with HL and the children with NH [$F(75,64)=0.7368$, $p=0.8845$]. These results suggest that children with longstanding HL may develop compensatory strategies that reduce the deleterious effects of HL on speech perception.

IV. DISCUSSION

Recall that the purpose of the present study was to examine the immediate and long-term effects of HL on the speech perception of children. To examine the immediate effects of HL, perception of meaningful and nonsense sentences was examined in NH children under conditions of simulated HL. It was hypothesized that their performance would be poorer in the simulated HL condition compared to quiet despite equivalent audibility in both conditions. Sig-

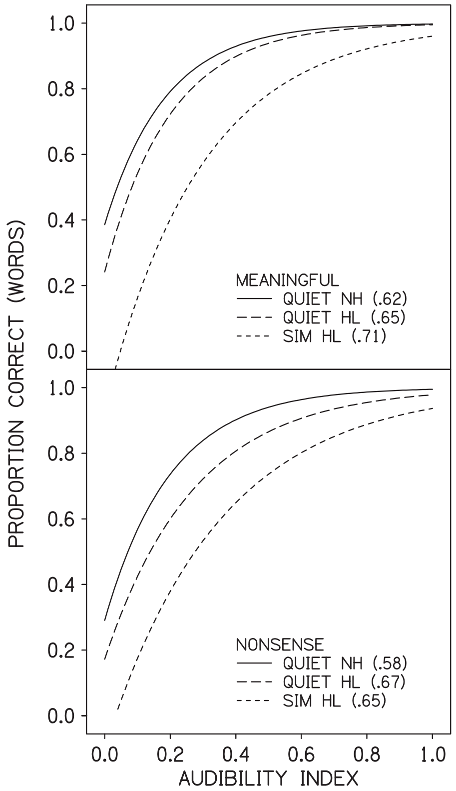

FIG. 5. Transfer functions showing the relation between performance and audibility for the meaningful sentences in the upper panel and for the nonsense sentences in the lower panel. Functions for the NH children (quiet NH—solid line), hearing-impaired children (quiet HL—long dashed line), and noise-masked NH children (Sim HL—short dashed line) are shown. Correlation coefficients (r^2) are provided for each transfer function.

nificant differences in performance were observed for the nonsense sentences but not for the meaningful sentences. These results suggest that when contextual information was provided, the presence of HL was not a determining factor. However, when the same words were presented in nonsense sentences, perception was no longer as simple, revealing the potential effects of HL.

Second, the long-term effects of HL were examined by comparing the performance of the children with actual HL to that of the children with simulated HL. It was hypothesized that the performance of the children with actual HL would be poorer than that of the children with simulated HL due to the long-standing effects of hearing impairment on the development of speech perception. For example, the presence of HL may have made certain acoustic elements of the speech signal inaudible over the long term, slowing their ability to decode the auditory signal and fill in the missing information. This would be particularly evident for speech in unpredictable contexts like the nonsense sentences used in this study. However, the results revealed no significant differences between the groups for either type of sentence suggesting that long-term HL did not further reduce their ability to perceive the sentences.

It is important to note, however, that children are often required to perceive more complex materials in more difficult listening conditions than those in the present study. For example, the speech materials used were short sentences composed of simple words. In a learning environment such as the classroom, children are expected to perceive new and more complex phrases every day. Likewise, the masking noise used for this study was chosen to simulate HL and to facilitate the presentation of equivalent sensation level in each condition. In the classroom, children must perceive speech in a variety of background competitors. Children's performance in more difficult listening situations may better reveal any effects of long-standing HL. The most striking example of this is a study by Crandell (1993) in which he examined sentence recognition in elementary school children with minimal HLs compared to children with NH. The sentences were presented in a multi-talker noise over a range of signal-to-noise ratios. Not only did the multi-talker noise mask the perception of the sentences, the phonological content of the babble offered contextual interference as well; similar to the kind of interference children encounter in the classroom. The children with HL showed significantly greater declines in performance with increases in signal-to-noise ratio compared to the children with NH. Moreover, the poorer performance of the children with minimal HL was substantial for school-age children. That is, although the children with NH could tolerate some levels of background noise (70% recognition in −6 dB SNR), the children with minimal HLs were nearly incapable of communicating in the same level of noise (38% recognition in −6 dB SNR).

Procedurally, the results of this study suggest that the immediate effects of HL may be simulated well in children using masking noise. This technique may prove useful for certain aspects of pediatric hearing research. Difficulty recruiting sufficient numbers of children with similar HLs is a common problem. Typically, a compromise is made in which one or more recruitment criteria are relaxed. For example, children over a wide range of ages may be recruited to examine a particular configuration of HL. For other studies, the degree and configuration of loss may be allowed to vary in order to examine children within a narrow age range. Although statistical procedures are available to accommodate for variability in age or hearing level, even larger numbers of children are required to meet the assumptions of the test statistic. As a result, research in children with HL is often underpowered and only applicable to a portion of the entire population. The results of this study suggest that this procedure may be useful for examining other aspects of auditory development and hearing impairment in larger numbers of children with NH.

Another important issue to consider is the use of an AI to compare the performance of the groups and listening conditions. It should be noted that the application of an AI in this context differs from that of the speech intelligibility index procedure provided in the American National Standards Institute (1997) standard. The speech intelligibility index was developed to reconcile stimulus audibility with performance so that speech perception may be predicted on the basis of audibility alone and eliminate the need for empirical testing. This approach is particularly attractive to clinicians and scientists who work with populations that are difficult to test (e.g., infants and young children). Many revisions to the speech intelligibility index have been proposed that adjust or change audibility values to more precisely coincide with performance. These revisions are in the form of factors (e.g., proficiency, desensitization, age, and HL) that adjust the audibility values, and therefore the transfer function, to better fit the performance data. It could be argued that the differences observed in the present study were due to the manner in which the AI was calculated. Although it may be possible to revise the AI calculation so that the transfer functions for each group and condition converge, that was not the purpose of the study. Instead, the same audibility procedure was applied in all conditions to determine the effects of elevated hearing thresholds on speech perception. The only factor accounted for in the calculation of audibility was for level distortion, which was appropriate given that the presentation levels were higher than most children with NH experience during speech perception. Factors associated with masking and near-threshold testing also may be applicable, however, the results are unlikely to change. That is, the long-term effects of HL on speech perception are minimal and the immediate effects of HL are more apparent for linguistically challenging materials.

Related to the calculation of audibility is the considerable variability observed in the performance of each group and in each listening condition. This kind of variability is commonly observed in this population (Stelmachowicz *et al.*, 2000; Scollie, 2008) and limits interpretation of the results. One possible cause for this variation may have been the manner in which the quiet and masked thresholds were matched. Specifically, thresholds were matched at octave intervals only. It is possible that the children with HL had inter-octave thresholds that varied somewhat in level resulting in more or less audibility than estimated. Because the same problem may occur if thresholds were obtained at more frequencies (e.g., 18 1/3-octave intervals), not to mention the impracticality of such an approach with children, a better solution may be to present the same frequency-shaped masking noise to both the children with NH and the children with HL. Dubno *et al.* (2000) used this procedure to elevate the thresholds of adults with NH and with HL to a specified level above target while preserving the configuration of HL. A similar approach in children may reduce undetected differences in hearing thresholds and equate AI across groups more precisely. This, in turn, may reduce some of the variability in performance at all levels of audibility.

V. SUMMARY

An experiment was conducted to determine the immediate and long-term effects of HL on the development of speech perception. The results suggest that childhood HL has the potential to delay or impair the development of speech perception as evidenced by the poorer performance of children in the simulated HL condition. However, children appear to develop compensatory strategies that are sufficient to overcome some of the deleterious effects of HL.

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Allen, P., and Wightman, F. (**1994**). “Psychometric functions for children’s detection of tones in noise,” J. Speech Hear. Res. **37**, 205–215.

American National Standards Institute (**1997**). Methods for calculation of the speech intelligibility index (ANSI S3.5-1997), American National Standards Institute, New York.

American National Standards Institute (**1999**). Maximum permissible ambient noise levels for audiometric test rooms (ANSI S3.1 1-1999), American National Standards Institute (ANSI), New York.

Blamey, P. J., Sarant, J. Z., Paatsch, L. E., Barry, J. G., Bow, C. P., Wales, R. J., Wright, M., Psarros, C., Rattigan, K., and Tooher, R. (**2001**). “Relationships among speech perception, production, language, hearing loss, and age in children with impaired hearing,” J. Speech Lang. Hear. Res. **68**, 264–285.

Boothroyd, A. (**1997**). “Auditory development of the hearing child,” Scand. Audiol. Suppl. **46**, 9–16.

Boothroyd, A., and Nittrouer, S. (**1988**). “Mathematical treatment of context effects in phoneme and word recognition,” J. Acoust. Soc. Am. **84**, 101–114.

Buss, E., Hall, J. W., III, and Grose, J. H. (**2009**). “Psychometric functions for pure tone intensity discrimination: Slope differences in school-aged children and adults,” J. Acoust. Soc. Am. **125**, 1050–1058.

Crandell, C. C. (**1993**). “Speech recognition in noise by children with minimal degrees of sensorineural hearing loss,” Ear Hear. **14**, 210–216.

Dirks, D. D., Bell, T. S., Rossman, R. N., and Kincaid, G. E. (**1986**). “Articulation index predictions of contextually dependent words,” J. Acoust. Soc. Am. **80**, 82–92.

Dubno, J. R., and Ahlstrom, J. B. (**1995**). “Masked thresholds and consonant recognition in low-pass maskers for hearing-impaired and normal-hearing listeners,” J. Acoust. Soc. Am. **97**, 2430–2441.

Dubno, J. R., Ahlstrom, J. B., and Horwitz, A. R. (**2000**). “Use of context by young and aged adults with normal hearing,” J. Acoust. Soc. Am. **107**, 538–546.

Dubno, J. R., and Schaefer, A. B. (**1992**). “Comparison of frequency selectivity and consonant recognition among hearing-impaired and masked normal-hearing listeners,” J. Acoust. Soc. Am. **91**, 2110–2121.

Dubno, J. R., and Schaefer, A. B. (**1995**). “Frequency selectivity and consonant recognition for hearing-impaired and normal-hearing listeners with equivalent masked thresholds,” J. Acoust. Soc. Am. **97**, 1165–1174.

Dunn, L. M., and Dunn, L. M. (**2006**). *Peabody Picture Vocabulary Test III* (American Guidance Services, Inc., Circle Pines, MN).

Elliott, L. L. (**1979**). “Performance of children aged 9 to 17 years on a test of speech intelligibility in noise using sentence material with controlled word predictability,” J. Acoust. Soc. Am. **66**, 651–653.

Fabry, D. A., and Van Tasell, D. J. (**1986**). “Masked and filtered simulation of hearing loss: Effects on consonant recognition,” J. Speech Hear. Res. **29**, 170–178.

Gershkoff-Stowe, L., and Smith, L. B. (**1997**). “A curvilinear trend in naming errors as a function of early vocabulary growth,” Cognit Psychol. **34**, 37–71.

Hawkins, J. E., and Stevens, S. S. (**1950**). “The masking of pure tones and of speech by white noise,” J. Acoust. Soc. Am. **22**, 6–13.

Hicks, C. B., and Tharpe, A. M. (**2002**). “Listening effort and fatigue in school-age children with and without hearing loss,” J. Speech Lang. Hear. Res. **45**, 573–584.

Holt, R. F., and Carney, A. E. (**2007**). “Developmental effects of multiple looks in speech sound discrimination,” J. Speech Lang. Hear. Res. **50**, 1404–1424.

Humes, L. E., Dirks, D. D., Bell, T. S., and Kincaid, G. E. (**1987**). “Recognition of nonsense syllables by hearing-impaired listeners and by noise-masked normal hearers,” J. Acoust. Soc. Am. **81**, 765–773.

Humes, L. E., Espinoza-Varas, B., and Watson, C. S. (**1988**). “Modeling sensorineural hearing loss. I. Model and retrospective evaluation,” J. Acoust. Soc. Am. **83**, 188–202.

Jerger, S. (**2007**). “Current state of knowledge: Perceptual processing by children with hearing impairment,” Ear Hear. **28**, 754–765.

Jerger, S., Tye-Murray, N., and Abdi, H. (**2009**). “Role of visual speech in phonological processing by children with hearing loss," J. Speech Lang. Hear. Res. **52**, 412–434.

Levitt, H. (**1971**). "Transformed up-down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.

Needleman, A. R., and Crandell, C. C. (**1995**). "Speech recognition in noise by hearing-impaired and noise-masked normal-hearing listeners," J. Am. Acad. Audiol **6**, 414–424.

Nittrouer, S., and Miller, M. E. (**1997**). "Developmental weighting shifts for noise components of fricative-vowel syllables," J. Acoust. Soc. Am. **102**, 572–580.

Pittman, A. L., Lewis, D. E., Hoover, B. M., and Stelmachowicz, P. G. (**2005**). "Rapid word-learning in normal-hearing and hearing-impaired children: Effects of age, receptive vocabulary, and high-frequency amplification," Ear Hear. **26**, 619–629.

Pittman, A. (**2008**). "Perceptual coherence in listeners having longstanding childhood hearing losses, listeners with adult-onset hearing losses, and listeners with normal hearing," J. Acoust. Soc. Am. **123**, 441–449.

Scollie, S., Seewald, R., Cornelisse, L., Moodie, S., Bagatto, M., Laurnagaray, D., Beaulac, S., and Pumford, J. (**2005**). "The desired sensation level multistage input/output algorithm," Trends Amplif. **9**, 159–197.

Scollie, S. D. (**2008**). "Children's speech recognition scores: The speech intelligibility index and proficiency factors for age and hearing level," Ear Hear. **29**, 543–556.

Sherbecoe, R. L., and Studebaker, G. A. (**2002**). "Audibility-index functions for the connected speech test," Ear Hear. **23**, 385–398.

Stelmachowicz, P. G., Hoover, B. M., Lewis, D. E., Kortekaas, R. W., and Pittman, A. L. (**2000**). "The relation between stimulus context, speech audibility, and perception for normal-hearing and hearing-impaired children," J. Speech Lang. Hear. Res. **43**, 902–914.

Stuart, A. (**2005**). "Development of auditory temporal resolution in school-age children revealed by word recognition in continuous and interrupted noise," Ear Hear. **26**, 78–88.

Studebaker, G. A., Gilmore, C., and Sherbecoe, R. L. (**1993**). "Performance-intensity functions at absolute and masked thresholds," J. Acoust. Soc. Am. **93**, 3418–3421.

Van Deun, L., van Wieringen, A., Van den Bogaert, T., Scherf, F., Offeciers, F. E., Van de Heyning, P. H., Desloovere, C., Dhooge, I. J., Deggouj, N., De Raeve, L., and Wouters, J. (**2009**). "Sound localization, sound lateralization, and binaural masking level differences in young children with normal hearing," Ear Hear. **30**, 178–190.

Wightman, F., Allen, P., Dolan, T., Kistler, D., and Jamieson, D. (**1989**). "Temporal resolution in children," Child Dev. **60**, 611–624.