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Age-Related Benefits of Digital Noise Reduction for Short-Term Word Learning in Children With Hearing Loss

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Purpose: To determine the rate of word learning for children with hearing loss (HL) in quiet and in noise compared to normal-hearing (NH) peers. The effects of digital noise reduction (DNR) were examined for children with HL.
Method: Forty-one children with NH and 26 children with HL were grouped by age (8–9 years and 11–12 years). The children learned novel words associated with novel objects through a process of trial and error. Functions relating performance across trials were calculated for each child in each listening condition and were compared.
Results: Significant effects were observed for age (older > younger) in the children with NH and listening condition (quiet > noise) in the children with HL. Significant effects of hearing status were also observed across groups (NH > HL), indicating that the children with HL required more trials to learn the new words. However, word learning improved significantly in noise with the use of DNR for the older but not for the younger children with HL. Hearing aid history and signal-to-noise ratio did not contribute to performance.
Conclusion: Word learning was significantly reduced in younger children, in noise, and in the presence of hearing loss. Age-related benefits of DNR were apparent for children over 10 years of age.

Key Words: children, hearing loss, noise reduction, word learning

Learning new words is a critical accomplishment of childhood that lays the foundation for language and literacy development. A broad and deep vocabulary allows children to speak effectively, read comprehensively, and write meaningfully. Although a number of factors are known to promote the learning of new words (e.g., age of the child, size of the child's vocabulary, similarity of the new word to other known words), hearing loss (HL) has been shown to pose a significant barrier. This notion is supported by evidence relating the severity of a child's HL to the size of his or her vocabulary (Briscoe, Bishop, & Norbury, 2001; Fellinger, Holzinger, Beitel, Laucht, & Goldberg, 2009; Kiese-Himmel, 2008; Sarant, Holt, Dowell, Rickards, & Blamey, 2008; Wake, Hughes, Poulakis, Collins, & Rickards, 2004). It has been shown that, on average, the vocabulary of school-aged children with mild-to-moderate HL is 2–3 years behind that of children with normal hearing (NH; Pittman, Lewis, Hoover, & Stelmachowicz, 2005). The effect of severe-to-profound HL is an even slower rate of vocabulary development that further widens the gap between children with HL and children with NH over time (Blamey et al., 2001). Taken together, it appears that mild-to-moderate degrees of HL delay vocabulary development, whereas more severe HL impairs it. Although the differences between chronological and vocabulary age may be negligible at younger ages, concerns for social, academic, and mental health problems (Fellinger et al., 2009) can occur for children with HL who are chronologically 12 years of age but have the vocabulary of a 9-year-old.

Unlike the disordered word learning of children with specific language impairment (SLI), the basis of poor word learning in children with HL appears to be the result of their impaired peripheral auditory systems. Specifically, word learning in children with SLI has been attributed, in large part, to impaired working memory (Alt, 2010). On the other hand, research has shown that the working memory of children and adults with

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HL is independent of hearing loss (Hansson, Forsberg, Lofqvist, Maki-Torkko, & Sahlen, 2004; Lyxell, Andersson, Borg, & Ohlsson, 2003; Zekveld, Deijen, Goverts, & Kramer, 2007). One could argue, however, that a degraded representation of a new word also affects working memory. Degraded perception of speech has been shown to cause poor phonological processing in children (Briscoe et al., 2001) and may prevent the cognitive processes that are triggered when a new word is perceived (see, e.g., Storkel & Lee, 2011). For example, the words *hat, sat,* and *fat* may be well-known to a child with HL, but each word contains low-level, high-frequency voiceless fricatives that may be difficult for a child to differentiate, even with amplification. Perception of a new word such as *shat* may be confused with these known words, thus resulting in misperception rather than a trigger for word learning. Therefore, the threshold for identifying a word as new is higher in children with HL. Even when a word is recognized to be new, multiple repetitions may be necessary to form a sufficient representation in order to differentiate it from other known words. This was demonstrated in children with HL and in children with NH who were asked to learn nonsense words that were subtly degraded by narrowing the bandwidth of the signal to that of typical hearing aids (Pittman, 2008). Word learning for both groups was significantly reduced, suggesting that a degraded signal can interfere with the word-learning process, even for children with NH.

Whereas standardized tests are used to quantify children's receptive and expressive vocabularies, paradigms focusing on the speed and accuracy of word learning have been developed to determine those conditions that promote or impede the word-learning process (Akhtar, 2005; Akhtar, Jipson, & Callanan, 2001; Dollaghan, 1985; Lederberg, Prezbindowski, & Spencer, 2000; Rice & Woodsmall, 1988). One such paradigm was used in a recent study to examine the effects of certain hearing aid characteristics on receptive word learning in children with HL compared to children with NH (Pittman, 2008). In this paradigm, nonsense words are assigned to novel objects that have no common name. Children play a computer game that requires them to learn the names of the objects through a process of trial and error. On each trial, the children listen to a novel word and then select an object. Reinforcement is awarded for correct selections only, providing the children with the information needed to learn. At the end of the test (about 15 min), a function representing the children's increasing performance over 100 or more trials is generated to determine the number of exposures needed to achieve a criterion level of performance. With this paradigm, the effects of hearing loss and listening conditions on the rate of word learning may be examined. For example, noise is considered to be one of the most adverse listening conditions for hearing aid users (Kochkin, 2002). One form of hearing aid technology that has the potential to benefit children with HL when they are in noise is *digital noise reduction* (DNR). The goal of this technology is to improve listening comfort and preserve or improve the perception of speech. The advantages of examining the effects of DNR on auditory skills such as word learning over traditional speech perception measures are many. First, perception of the novel words does not require previous knowledge of or experience with the language. Second, a period of acclimatization with a particular form of signal processing is not necessary. Third, considerable data may be collected in a short period of time. And finally, word learning—similar to speech perception—has high face-validity in pediatric populations.

DNR

Chung (2004) provides a thorough description of the signal detection, analysis, decision rules, and execution of DNR in commercially available hearing aids. In general, alterations to the output of the hearing aid occur in selected frequency bands or over the entire frequency spectrum when steady-state noise is detected at the input to the hearing aid. The manner in which noise reduction is achieved varies across hearing aid makes and models (Hoetink, Korossy, & Dreschler, 2009), but the most common approach is an overall decrease in output. The effects of DNR are also more pronounced for steady-state noise than for speech signals because steady-state noise is more easily detected and managed by DNR algorithms (Bentler & Chiou, 2006; Ricketts & Hornsby, 2005).

Despite the reduction in overall amplification, research has shown that speech perception in noise and speech reception threshold with DNR are well preserved in adults (Auriemmo et al., 2009; Bentler, Wu, Kettel, & Hurtig, 2008; Nordrum, Erler, Garstecki, & Dhar, 2006; Peeters, Kuk, Lau, & Keenan, 2009; Ricketts & Hornsby, 2005; Stelmachowicz et al., 2010). Similar results were found in two studies conducted in children. Stelmachowicz and colleagues (2010) examined speech perception in 16 children between the ages of 5 and 10 years with mild to moderately severe HL. The authors used behind-the-ear hearing aids having DNR technology that uses a modified spectral subtraction algorithm performed independently in 16 frequency bands. The aids were fit to each child according to DSL targets (Scollie et al., 2005; Seewald, Moodie, Scollie, & Bagatto, 2005) and were verified using real-ear measures. The children's perception of nonsense syllables, monosyllabic words, and sentences in noise was examined as a function of age and DNR (activated vs. deactivated). Main effects of age and stimulus condition were observed; however, no effect of noise reduction was found. As with adults, the results suggest that children's performance with DNR is preserved despite the reduction in overall amplification.

Auriemmo et al. (2009) reported similar results for speech recognition in 19 children with mild to moderately severe sensorineural HL between the ages of 6 and 12 years. The authors used behind-the-ear hearing aids employing a multichannel adaptive DNR algorithm that reduced the gain independently in 15 frequency bands. The overall signal-to-noise ratio (SNR) benefit provided by directional microphones, as well as the benefit of DNR in quiet and at three SNRs (+5 dB, 0 dB, and −10 dB), was determined. Although a significant SNR improvement was observed for the directional microphone condition over the omnidirectional condition, no differences in performance were observed with the use of DNR. Also, standardized tests of language development revealed that the children were not adversely affected by adaptive directional microphones and DNR after using the technology for a 1-year period.

Although it appears that DNR preserves speech perception in children and adults, a significant weakness of previous studies is that the parameters of the acoustic signal provided by DNR were not reported—that is, the amount by which the amplified signal was attenuated by DNR and the signal level relative to the noise were not reported. It is possible that little effect was observed because little noise reduction occurred. It is also possible that DNR imposed significant reductions on the amplified signal but performance was preserved due to the redundancy of speech. It has been well established that speech perception is robust and can withstand substantial degradation of the speech signal with little effect on perception (Remez, Pardo, Piorkowski, & Rubin, 2001; Walden, Prosek, & Worthington, 1975). When perception is further supported by the context of the message, the listener's familiarity with the speaker, and his or her knowledge of the topic, the listener with HL is better able to fill in the missing auditory information to perceive the message with confidence. However, the benefits of DNR may not be as apparent for auditory tasks that are not supported as well as speech perception. For children, learning new words is one such task—one of the most important auditory tasks that they must perform in order to communicate effectively.

The purpose of the present study was twofold. First, the impact of noise on children's ability to learn new words was determined for children with NH and children with HL. It was hypothesized that learning would decrease in noise for both groups—and more so for the children with HL. Second, the impact of DNR on word learning in children with HL was examined. It was hypothesized that the reduction in overall amplification imposed by DNR would slow the learning rate in noise. To capture the known effects of age on word learning, two age groups of children were recruited (ages 8–9 years, ages 11–12 years). These groups represent the period of greatest vocabulary growth (Anglin, Miller, & Wakefield, 1993; Johnson & Anglin, 1995), a period in which Bloom (2001) estimated that approximately 12 new words are learned per day (p. 44). It was hypothesized that word learning would be directly related to receptive vocabulary over and above hearing status.

Method

Participants

Forty-one children with NH (22 boys, 19 girls) participated in this study. Children were recruited on the basis of chronological age to form two age groups: a younger group consisting of 20 children between the ages of 8 and 9 years (*M* = 9;0 [years;months], *SD* = 0.7, range = 8;1–9;11) and an older group of 21 children between the ages of 11 and 12 years (*M* = 11;11, *SD* = 0.65, range = 11;0–12;11). On the day of testing, all children had hearing thresholds ≤ 20 dB HL bilaterally at octave frequencies between 0.25 kHz and 8 kHz. Normal middle-ear status was confirmed with acoustic immittance measures. These children served as the control group.

Children with HL were enrolled in the study if they were eligible for monaural or binaural amplification. The experimental group comprised 26 children (11 boys, 15 girls) with mild to moderately severe HL. Thirteen children were between the ages of 8 and 10 years (*M* = 9;1, *SD* = 0.55 range = 8;1–9;11), and 13 were between the ages of 11 and 12 years (*M* = 11;11, *SD* = 0.66, range = 11;0–12;11). It was confirmed, through *t* tests, that there were no differences in age between the NH and HL groups for the younger, $t(31) = -0.662$, $p = .50$, and older, $t(32) = 0.304$, $p = .763$, children. Average age of HL identification was 3;1, with a range of 0 (birth) to 6 years of age. All but one of the children wore personal hearing aids. For those children having personal hearing aids, average age at amplification was 4;4, ranging from 6 months to 8 years of age. Length of amplification for these children ranged from 1;6 to 11;0, with an average of 5;11. Only one child wore hearing aids having DNR enabled in a dedicated program.

On the day of testing, the participants received a full hearing evaluation, which included otoscopy, tympanometry, and pure-tone air- and bone-conduction audiometry. Children whose hearing thresholds were unchanged since their last hearing evaluation did not receive bone-conduction testing. Table 1 contains the hearing thresholds of each child in the younger and older groups at octave frequencies between 0.25 kHz and 8 kHz. The children's gender, chronological age, type of hearing loss in each ear, and ears amplified during testing are also provided. Figure 1 shows the hearing thresholds of each child as a function of frequency for the right and left ears in the upper and lower panels, respectively. Average hearing levels (± 1 *SD*) for the younger group

Table 1. Demographic characteristics of the children with hearing loss (HL).

			Hearing threshold: Right ear (dB HL)						Hearing threshold: Left ear (dB HL)						Loss				
Participant	Gender	Age (yrs)	0.25	0.50	1	2	4	8	0.25	0.50	1	2	4	8	R	L	ID age (yrs)	HA age (yrs)	Amp config
8–9 years of age																			
1	Male	8.92	35	40	45	65	65	85	70	70	80	90	115	NR	S	S	1.0	1.5	M
2	Female	9.17	25	45	55	80	65	70	30	50	60	65	70	70	S	S	3.0	3.0	B
3	Female	9.75	35	30	25	60	60	60	40	40	40	70	65	60	S	S	5.0	5.0	B
4	Male	9.33	15	20	45	55	60	65	0	15	45	50	50	50	S	S	1.5	5.0	B
5	Female	9.75	15	15	30	50	50	45	10	15	35	50	50	50	S	S	4.0	7.0	B
6	Female	9.58	50	50	60	65	65	65	45	55	60	60	60	60	S	S	2.0	2.0	B
7	Male	9.00	35	35	50	55	55	40	40	50	60	45	55	50	S	S	3.0	3.0	B
8	Female	9.42	20	15	35	45	25	5	15	25	50	50	40	45	S	S	5.0	8.0	B
9	Female	8.17	20	30	45	40	35	45	20	35	45	50	40	45	S	S	3.0	3.0	B
10	Male	8.92	50	45	35	40	30	20	30	30	35	35	30	10	C	C	6.0	6.0	B
11	Female	9.17	45	45	40	45	20	25	50	65	40	55	25	25	C	C	4.0	4.0	B
12	Male	9.92	35	45	40	30	40	50	25	25	45	30	30	55	S	S	0.0	1.5	B
13	Female	8.17	45	55	55	40	10	10	5	−5	−5	−5	−5	0	S	N	4.5	5.0	M
Average		9.17	33	36	43	52	45	45	29	36	45	50	48	43			3.2	4.2	
11–12 years of age																			
1	Male	11.08	20	25	25	65	NR	NR	10	15	15	15	80	85	S	S	3.0	8.0	B
2	Female	12.92	15	10	40	65	85	85	10	25	40	60	85	80	S	S	5.0	6.0	B
3	Male	11.42	10	15	35	85	75	65	15	10	10	10	0	5	S	N	4.0	8.0	M
4	Female	12.08	30	15	15	65	80	80	30	15	0	−5	75	70	S	S	5.0	6.0	B
5	Female	12.00	25	40	65	80	75	70	30	45	55	60	75	75	S	S	0.0	7.0	B
6	Female	11.75	30	30	40	50	40	30	35	35	50	55	40	30	S	S	3.0	3.0	B
7	Male	12.67	30	50	65	70	65	20	50	45	65	70	65	20	S	S	1.5	1.8	B
8	Male	11.17	35	40	40	80	75	70	65	65	60	80	70	55	S	S	0.0	0.5	B
9	Female	12.92	50	60	75	80	65	70	50	65	70	75	65	70	S	S	2.0	2.0	B
10	Female	12.50	45	40	50	50	40	10	75	85	75	85	75	75	M	M	4.0	5.0	B
11	Male	11.75	10	10	10	0	15	25	45	30	35	40	85	NR	N	S	4.0	n/a	M
12	Female	11.50	25	30	45	50	40	40	30	35	40	40	35	40	S	S	5.0	5.0	B
13	Female	11.08	65	70	75	75	65	70	60	65	80	80	75	70	S	S	2.0	2.0	B
Average		11.91	30	33	45	63	60	53	39	41	46	51	63	58			3.0	4.5	

Note. S = sensorineural; M = mixed; C = conductive; N = normal; ID age = age at identification (in years); HA age = age when fit with hearing aids (in years); amp config = amplification configuration; B = binaural; M = monaural; n/a = "not available." Children are listed in order of the overall signal-to-noise ratio improvement received with the use of digital noise reduction (see Figure 4). Blank cells indicate "not applicable."

(filled symbols) and older group (open symbols) are shown in each panel. On average, the hearing thresholds were similar through 1 kHz, with somewhat poorer thresholds occurring at higher frequencies for the older children. The variability in HL configuration across children is typical of this population and is consistent with that reported in previous studies in this age group (Auriemmo et al., 2009; Delage & Tuller, 2007; Gravel, Fausel, Liskow, & Chobot, 1999; Jerger, Martin, Pearson, & Dinh, 1995; Jutras & Gagne, 1999; Scollie, Seewald, Moodie, & Dekok, 2000; Stelmachowicz et al., 2010; Stelmachowicz, Pittman, Hoover, & Lewis, 2002; Stelmachowicz, Lewis, Choi, & Hoover, 2007). Acoustic immittance was consistent with the middle-ear status of each child. All of the children (NH and HL) were enrolled in the grade that was appropriate for their age in public elementary schools or through home schooling.

Prior to testing, the receptive vocabulary of each child was determined using the Peabody Picture Vocabulary Test—III (Form IIIB; Dunn & Dunn, 2006). Recall that standardized measures of receptive vocabulary can reveal the long-term effects of childhood HL when compared to those of NH peers (Blamey et al., 2001; Pittman et al., 2005). Figure 2 shows the results of the PPVT–III as a function of chronological age for the children with NH (filled symbols) and the children with HL (open symbols). PPVT age, standard score, and raw score are shown in the upper, middle, and lower panels, respectively. Asterisks indicate the children with HL who did not have a bilateral sensorineural hearing loss and who

Figure 1. Hearing threshold levels (in dB HL) as a function of frequency (kHz) for the right ears (upper panel) and left ears (lower panel) of the children with hearing loss (HL; dotted lines). Dashed lines represent ears that were not amplified. Average hearing thresholds in each ear for the 8- to 9-year-olds (filled circles) and the 11- to 12-year-olds (open circles) are also shown.

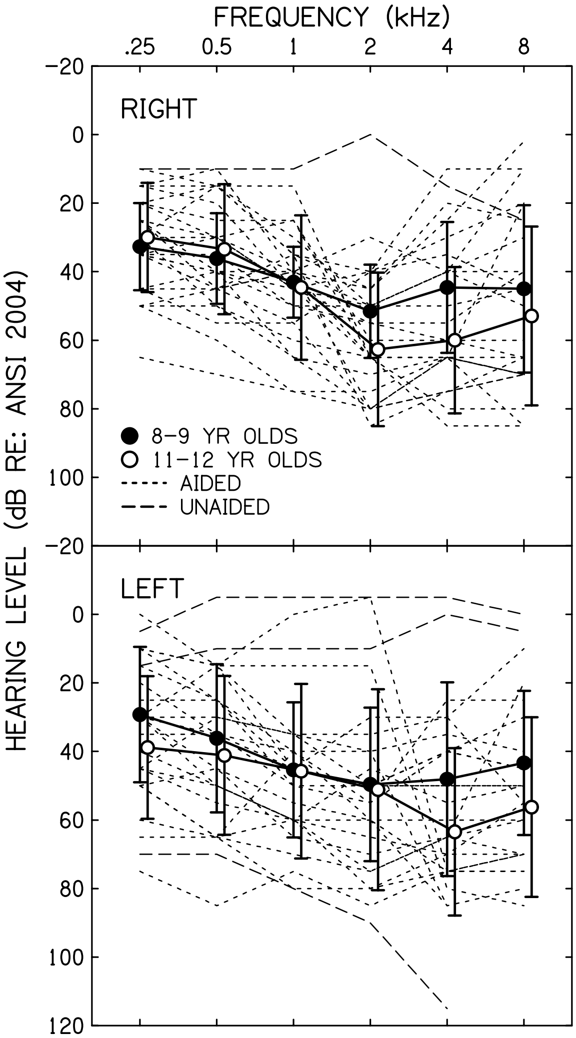
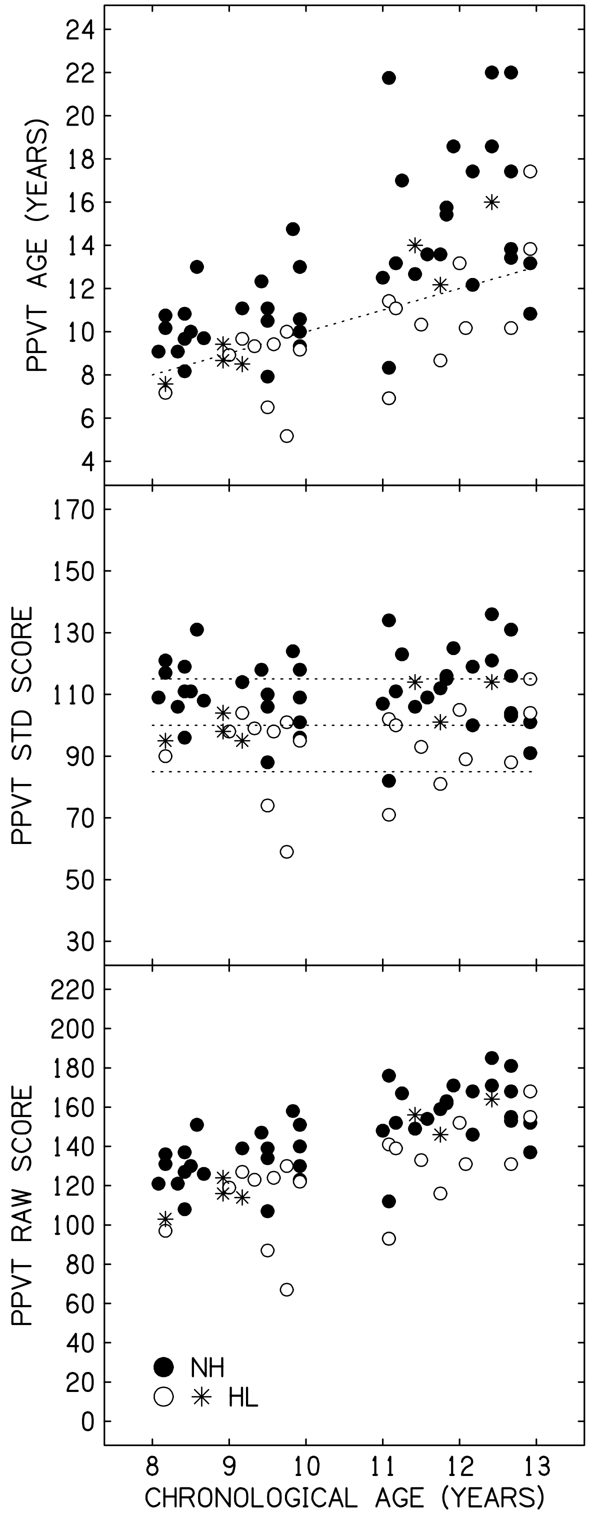


Figure 2. Peabody Picture Vocabulary Test—III (PPVT–III) age, standard (STD) score, and raw score as a function of age group for the children with normal hearing (NH; filled symbols) and the children with HL (open symbols). Asterisks indicate children with monaural amplification. Dotted lines show 1:1 correlation of vocabulary and chronological age (upper panel) and 1 *SD* of the mean (middle panel).



may be identified from Table 1 using the chronological age. For example, two children aged 8;11 scored similarly on the PPVT–III, even though one child had a moderate-to-profound mixed loss and the other had a mild conductive loss. These results show that the receptive vocabulary of the children with NH is greater than that of the children with HL, with some overlap between the two. A two-way analysis of variance (ANOVA) confirmed significant main effects of age, $F(1, 63) = 38.203, p < .001$, and hearing status, $F(1, 63) = 16.917, p < .001$. The lack of an Age × Hearing Status interaction, $F(1, 63) = 0.941, p = .336$, indicates a similar difference in vocabulary level for each age group. The difference is on the order of 3 years, which is consistent with previous studies (Pittman et al., 2005; Stelmachowicz, Pittman, Hoover, & Lewis, 2004).

Amplification

Each child was fitted with behind-the-ear hearing aids for use during the experimental tests (see Table 1). The DNR feature in this hearing aid consists of two independent DNR algorithms that operate simultaneously in each of 16 channels (see Mueller, Weber, & Hornsby, 2006, for a full description). The first is a modulation detection algorithm that causes the gain within each channel to be reduced when steady-state noise is detected. Gain is reduced independent of the signal level in the channel and can be adjusted with the manufacturer's programming software. The second DNR algorithm employs technology similar to a Wiener filter, which calculates the SNR and filter coefficient for each channel by tracking the envelope of the signal within the channel. This feature operates continuously regardless of the input signal (speech or noise) to the channel. Direct measures of the DNR feature in the hearing aids used in the present study showed an attack time of 3.2 s after the onset of steady-state, broadband noise and activated at input levels as low as 40 dB SPL. Effective gain reduction for the 50 dB SPL noise level employed during the word-learning tasks was 7 dB when set to maximum noise reduction.

The hearing aids were fitted using the child's personal earmolds. Four children did not have their personal earmolds with them at the time of testing, so temporary molds (Comply, Snap Tips) were used. The hearing aid manufacturer's software was used to program and fine-tune the devices based on the simulated real-ear measures (SREM) performed with the Verifit (Audioscan, VF-1) hearing aid test system. Following the manufacturer's instructions, individual real-ear-to-coupler differences—as well as the child's hearing thresholds—were obtained and were entered into the Verifit. The output of the hearing aids was adjusted to within 5 dB of the targets prescribed for average (65 dB SPL) and soft (50 dB SPL) conversational speech by the Desired Sensation Level (DSL [i/o] 5.0) fitting algorithm (Scollie et al., 2005; Seewald et al., 2005). Real-ear measures were obtained for the first five children to confirm that the SREM procedure provided an accurate estimate (± 2 dB) of real-ear amplification. Thereafter, all hearing aids were programmed using the SREM function only.

For this investigation, two active programs were created in each hearing aid. In Program 1, all advanced signal-processing features offered in the hearing aid were disabled, including Speech and Noise Management (DNR), Sound Smoothing (reduction of impulse noises), eWind Screen (reduction of wind noise), and Feedback Blocker (feedback management). In Program 2, all advanced signal-processing features remained disabled with the exception of the Speech and Noise Management feature, which was set to maximum. The Speech-in-Noise-Only option, which activates the noise reduction feature only when both speech and noise are present, was disabled. This caused the hearing aid to activate the DNR feature whenever noise was detected, regardless of whether speech was present. The output of each program was equated to provide the same audibility in quiet with or without DNR activated.

The user controls for this hearing aid included a program button and a volume control. The hearing aids were set to indicate when it was in Program 1 or 2 by generating one or two beeps, respectively. The beeps were set to occur at a frequency and output level that was audible to the child. The range of the volume control was set to 0 (i.e., deactivated), which meant that it served as an on/off switch only.

Prior to testing, each child was familiarized with the hearing aids and was trained to select the required program when directed to do so. Because all but one of the children were experienced hearing aid users, they required minimal orientation to the device. This experience allowed them to focus their attention on the "program" button, which was new to many of them. The children were required to indicate the number of beeps that they heard when the hearing aids were changed from one program to the next. Because the hearing aids were equipped with a feature that linked the two hearing aids (E2E), changing the program in one hearing aid also changed the program in the other aid, causing the child to hear one or two beeps in each ear at nearly the same time. Most of the children were able to perceive the correct number of beeps generated by the hearing aid in each ear, whereas some did not. For those children, the examiner adjusted the hearing aids during testing. All other children adjusted the hearing aids by pressing the program on both aids.

Stimuli

Three sets of five nonsense words were created for this study. The words are listed in Table 2 with their orthographic and phonetic transcriptions from which the positional and biphone probabilities were calculated (Vitevitch & Luce, 2004).[1] All of the words were two syllables in length and were pronounced with the stress on the first syllable, as is typical of two-syllable English words. The words within each list contained the same two vowels in the first and second syllables so that

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[1] Phonotactic and biphone probability is the likelihood of certain phoneme sequences occurring in a particular order within a given language (Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997; Vitevitch, Luce, Pisoni, & Auer, 1999). Research has shown that word learning in children is faster for higher probability words (Storkel, 2001, 2003).

Table 2. Nonsense words used during the dynamic word-learning task.

		Phonotactic probability	
Phonetic	**Orthographic**	**Positional**	**Biphone**
	List 1		
destɪn	daystin	.3642	.0232
gesmɪt	gaysmit	.3084	.0056
mestɪl	maystill	.3169	.0261
teskɪt	tayskit	.3365	.0058
kestɪl	kaystill	.3524	.0254
	List 2		
smɛntɑs	smentos	.3436	.0132
pɛdtɑn	pedton	.3513	.0080
dɛpmɑst	depmost	.3394	.0187
sɛntɑp	sentop	.3585	.0333
kɛnsɑm	kensom	.3307	.0384
	List 3		
sɑθnəd	sothnud	.3347	.0081
dɑztəl	doztul	.3425	.0146
fɑsnəʃ	fosnush	.3345	.0073
stɑmən	stomun	.3445	.0455
hɑmtəl	homtul	.3594	.0212

Note. Phonetic and orthographic transcriptions are provided for each word in addition to the total positional and biphone phonotactic probability.

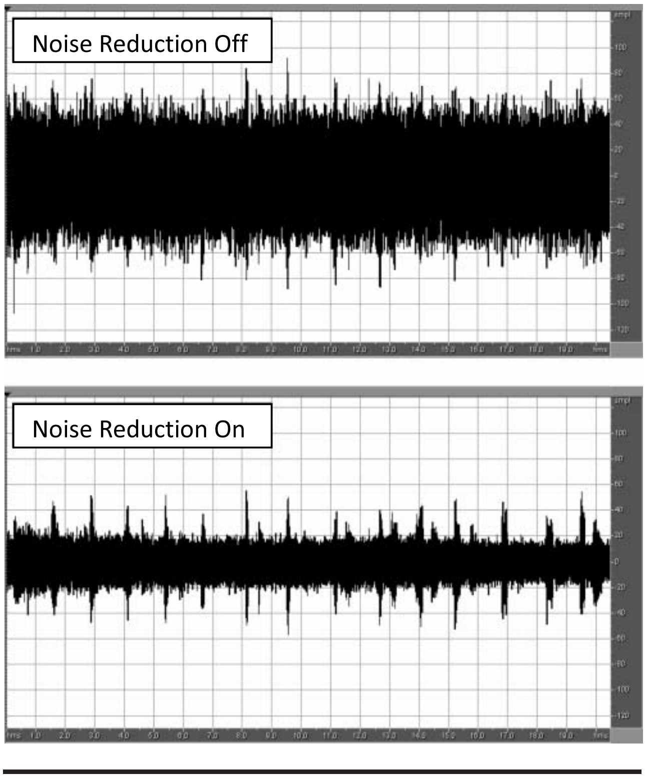
learning would depend on the perception of the lower-level consonants rather than the louder vowels. Consonant phonemes that occur frequently in English (Denes, 1963) were represented multiple times within each list. In this way, the words contained both unique and similar acoustic phonetic information, requiring the children to use more than one phoneme to identify any given word (Pittman, 2008; Stelmachowicz et al., 2004).

Stimuli were spoken by a female talker with a standard American English dialect. Recordings were made at a sampling rate of 22.050 kHz using a microphone with a flat frequency response to 10 kHz. The words were concatenated (removing all silent gaps), equated for root-mean-square level, and saved in separate audio files. Periods of silence were added to the beginning and end of each file so that each file was 2000 ms in duration. For the experiment, the words were mixed with a continuous, steady-state, broadband noise having a flat frequency spectrum ranging from 0.2 kHz to 10 kHz. Stimuli were presented in the sound field at an overall level of 50 dB SPL at the calibrated position and at an SNR of 0 dB. This speech and noise level was sufficient to activate the DNR feature but was low enough to minimize the incidence of compression limiting. In a sound-treated room, 50 dB SPL is equivalent to quiet conversational speech. The children's task was to learn the set of words presented in quiet and another set of words presented in noise. The children with NH learned two sets of words (one in quiet and one in noise), whereas the children with HL learned three sets of words (one in quiet, one in noise, and one in noise with the DNR activated). The word lists were counterbalanced across listening conditions, and the order of testing was counterbalanced across children.

DNR

Figure 3 shows the amplified waveforms for one child (15 stimuli). The stimuli and noise are shown with DNR off (upper panel) and with DNR on (lower panel). Although the nominal SNR was 0 dB for this experiment, the effective SNR for each child with HL can differ because of noise introduced by the hearing aid during amplification. Therefore, the effective SNR received by each child with HL was calculated with and without the DNR feature engaged. An inversion technique described by Souza, Jenstad, and Boike (2006) was used to separate the speech signal from the noise. This procedure requires three audio files containing (a) the speech and noise stimuli as they were used in the study (original speech + original noise), (b) the noise inverted and mixed with

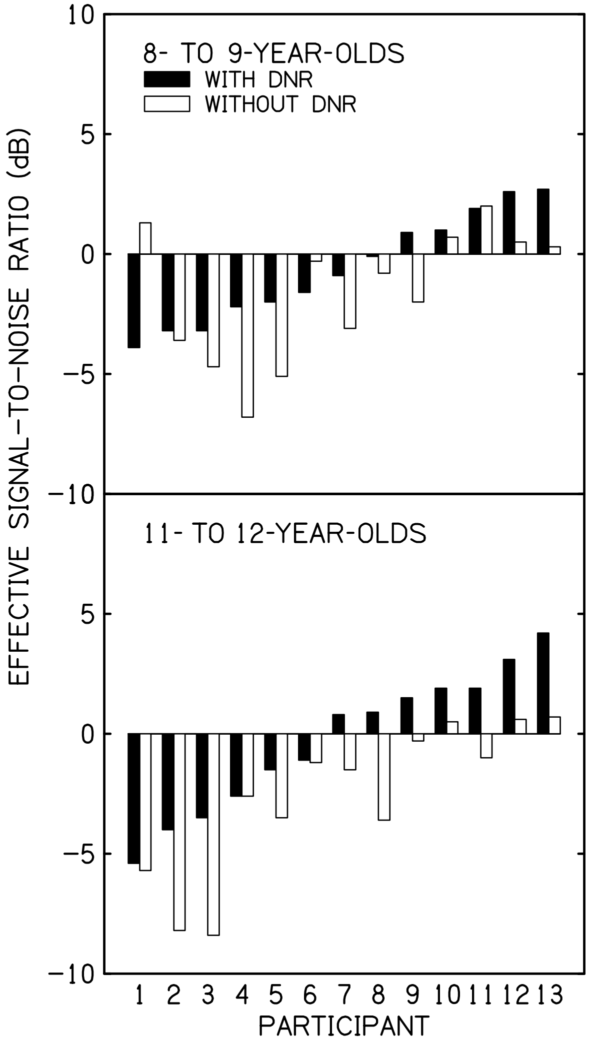
Figure 3. Waveforms showing the 15 novel words embedded in broadband noise at 0 dB SPL. The upper panel shows the stimuli amplified without digital noise reduction (DNR), and the lower panel shows the same stimuli amplified with DNR.



the original speech (original speech + inverted noise), and (c) the speech inverted and mixed with the original noise (inverted speech + original noise). The audio files were routed to a hearing aid test chamber (Verifit [Audioscan, VF-1]) where the output of the hearing aid was captured in a 2-cm^3 coupler (Frye, HA-2) with an appropriate adaptor for a probe microphone (Etymotic, ER-7C). The output of the probe microphone was routed to a SoundDelux soundcard in a desktop computer. Custom software was used to play the stimuli and record the output simultaneously. The recorded audio files were imported to an audio editor program (Adobe Audition, Version 1.5). Effective SNR was determined by mixing the first recorded audio file (original speech + original noise) with each of the other two files. Mixing caused the original and inverted components to cancel, whereas the amplitude of the in-phase component was doubled (6 dB). The overall level of the long-term average spectrum of the isolated speech and noise components was then calculated after applying a 6-dB correction. These measures revealed a decrease of 5.1 dB for the younger children and 5.3 dB for the older children when the DNR feature was engaged.

Figure 4 shows the effective SNR of the stimuli that each child with HL received from the hearing aid with and without DNR for the 8- to 9-year-olds (upper panel) and for the 11- to 12-year olds (lower panel). Overall SNR for the right and left hearing aids were averaged, with the exception of the three children who were aided monaurally. The children are listed in order of overall SNR achieved with DNR from least to greatest. This order was also used in Table 1 so that overall SNR could be compared to the children's hearing thresholds. The effective SNR ranged from –8.4 dB to 4.2 dB across conditions for the nominal 0 dB SNR presentation. Overall SNR improved when DNR was activated for all but a few children. The average effective SNR without DNR was –1.7 dB and –2.6 dB for the younger and older children, respectively. When DNR was activated, the average effective SNR was 0.6 and –0.3 dB for the younger and older children, respectively, for an average improvement of 2.3 dB for both groups. No correlation was found between overall SNR and pure-tone average hearing thresholds (averaged across ears) with DNR activated, $r = .291$, $p = .150$, or when DNR was deactivated, $r = .215$, $p = .291$.

Figure 4. Effective signal-to-noise ratio (in dB) that each child received with DNR (filled bars) and without DNR (open bars) for the 8- to 9-year-olds (upper panel) and the 11- to 12-year-olds (lower panel). The children are listed in order of signal-to-noise ratio achieved with the DNR ordered from least to greatest. The children are listed in the same order in Table 1.

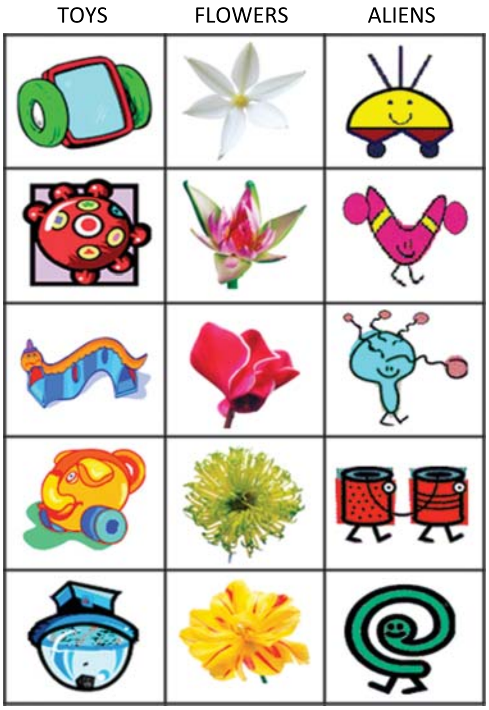


Dynamic Word Learning Task

The children's task was to learn the object or character to which a nonsense word belonged using an interactive computer game that promoted learning through a process of trial and error. During the game, a nonsense word is randomly selected and presented to the participant. He or she must then select one of five buttons displayed on the left side of a computer screen. Each button displays a picture of a nonsense object or character having no common name. Reinforcement for accurate selections is provided via a video game displayed on the right side of the computer screen (e.g., a piece of a puzzle was added to a picture). Reinforcement is not provided for incorrect responses. This trial-and-error process required the children to remember both their correct and incorrect selections in order to advance through the games.

Three sets of five pictures each were used and are displayed in Figure 5. Each set of pictures was internally consistent and represented toys, flowers, and aliens. In the event that a picture–word association was more salient

Figure 5. Visual stimuli used as referents for the nonsense words.



than another or that one picture was simply more appealing to the children than the others, the nonsense word associated with each picture was systematically alternated across children, and the pictures were counterbalanced across word lists. This reduced the impact of possible picture or word preference by distributing the effect across listening conditions.

Procedure

All testing was conducted in a sound-treated booth in the presence of two examiners. The first managed the experimental equipment and monitored the child's performance. The second examiner familiarized the child with the game and remained with the child during testing. The child was seated at a small table approximately 1 m from a loudspeaker at 0° azimuth. The stimuli were presented through the loudspeaker using custom software on a standard desktop computer. Although the temporal parameters of the experiment were controlled by the laboratory software, the children's responses were self paced—that is, a stimulus file was presented (2,000-ms duration), the children responded at their own pace (15-s response window), reinforcement was provided when appropriate, and the next stimulus was presented after a short delay (1,000 ms).

A brief practice session involving simple shapes associated with three nonsense words was used to familiarize the children with the task. The following instructions were given to the child:

> You are going to hear some silly names. Your job is to choose the picture on the screen that has that name by touching it with your finger or clicking on it with a mouse. If you choose the right picture, the game on the screen will play. If not, nothing will happen, and you will hear the next silly name. Don't be surprised if it takes a little while to figure out the name that goes with each picture.

Five repetitions of each word were randomly presented to the children for a total of 15 trials (< 2 min). When the children were comfortable with the game format, testing for the experimental conditions proceeded. Each word was presented 20 times for a total of 100 randomized trials (5 Words × 20 Repetitions). Testing lasted approximately 10 min per listening condition. Children were provided breaks as necessary and were paid for their participation according to the procedures outlined by the Institutional Review Board at Arizona State University.

Analysis

To characterize each child's word learning in the quiet and noise listening conditions, the trial-by-trial data were reduced to 10 bins of 10 trials each. Each trial was considered to be either correct or incorrect, and the proportion of correct responses within each block of 10 trials was calculated. For example, if a child responded correctly to two of the 10 trials, the score for that bin was 0.20. Figure 6 shows the data for an 11-year-old child with NH learning in the quiet listening condition. The trial blocks are labeled according to the midpoint of the block (e.g., 15 is the midpoint between Trials 10 and 20). The data were then fit with the following exponential growth function:

$$P_c = 1 - 0.8e^{-n/c}, \tag{1}$$

where P_c is the probability of a correct answer, *1 – 0.8* reflects chance performance for this task (20%), e is 2.718…, n is the midpoint of the trial block (5, 15, 25, etc.), and c is the time constant of the process. When $n = 0$ (beginning of the test), $Pc = 0.2$, with the curve growing from that raised floor in a smooth fashion to 1.0. When the number of trials equals the time constant ($n = c$), performance is approximately 70% (70.57%) correct. This was accomplished by adjusting estimates of c to minimize the sum of the squared deviations between the observed data and the points predicted. The dashed line in Figure 6 represents the point at which $n = c$ (or, 70% correct). In this example, 67 trials were required to achieve the criterion level of performance. The advantage of using this approach was that all data points in the learning process contributed to the determination

Figure 6. Results for one 8-year-old child with NH in the quiet listening condition. Performance is plotted as a function of trial block. Each block contains 10 trials and is labeled according to the midpoint of the block (e.g., 15 is the midpoint between 11 and 20). The solid line represents performance predicted by the learning function.

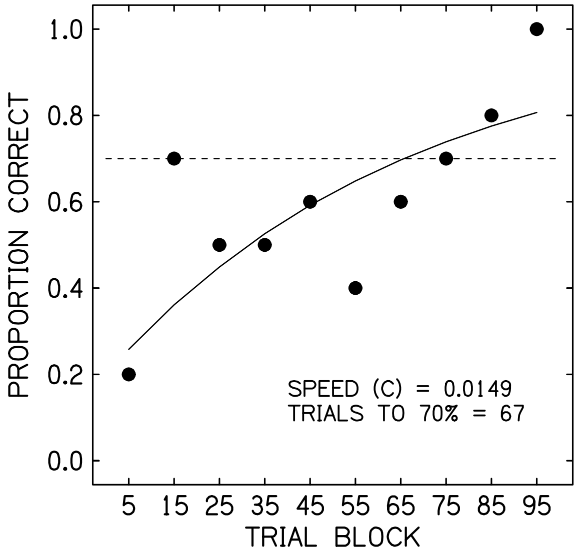
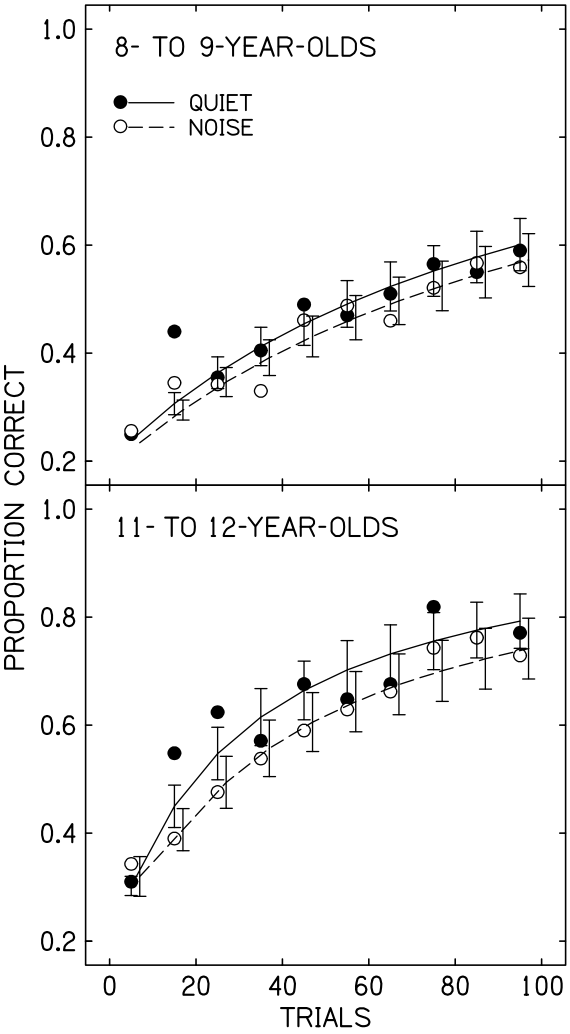


Figure 7. Averaged learning functions (±1 *SE*) for the two groups of children with NH—the 8- to 9-year-olds (upper panel) and the 11- to 12-year-olds (lower panel). Solid and dashed lines represent quiet and noise listening conditions, respectively. Data points are the averaged performance for each trial block.



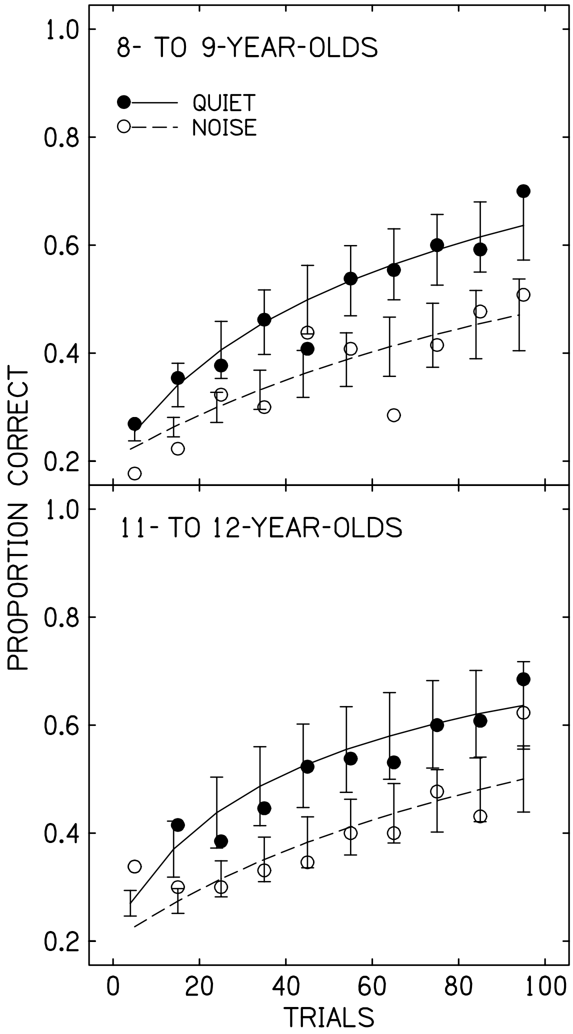
of the learning function and the time constant. The learning functions enabled individual and group performance to be evaluated across trials, whereas the number of trials needed to achieve the criterion performance provided a tangible point of reference with which to characterize the effects of hearing status and listening condition.

Results

Recall that the first goal of this study was to determine the impact of noise on children's ability to learn new words. Figure 7 shows proportion correct as a function of trial for the children with NH. Results for the 8- to 9-year-old children are shown in the upper panel, and results for the 11- to 12-year-old children are shown in the lower panel. The filled and open symbols are average proportion correct for each trial block in the quiet and noise listening conditions, respectively. The average learning functions (± 1 *SE*) are also shown for the quiet (solid line) and noise (dashed line) listening conditions. Although the performance of the younger children was poorer than that of the older children, little difference was observed between the quiet and noise listening conditions for both groups. Figure 8 shows proportion correct as a function of trial for the children with HL using the same convention as that used in Figure 7. Overall, performance was similar across age groups, with better performance in quiet and poorer performance in noise.

Effects of hearing status and listening condition were determined using repeated measures ANOVAs. Listening condition (quiet, noise) and trial block were entered as within-subjects factors, and hearing status (NH, HL) and age group (8–9 years, 11–12 years) were entered as between-subjects factors. The variable trial block did not meet the assumption of homogeneity of variance according to Mauchly's test of sphericity (Mauchly, 1940). The degrees of freedom were adjusted using the Greenhouse–Geisser correction for this and all other analyses. Significant main effects were observed for hearing status, $F(1, 58) = 5.073$, $p = .028$, $\eta^2 = .08$, $\beta = .601$; age group, $F(1, 58) = 5.595$, $p = .021$, $\eta^2 = .088$, $\beta = .643$; listening condition, $F(1, 58) = 7.606$, $p = .008$,

Figure 8. Averaged learning functions (±1 *SE*) for the the two groups of children with HL—the 8- to 9-year-olds (upper panel) and the 11- to 12-year-olds (lower panel). Solid and dashed lines represent quiet and noise listening conditions, respectively. Data points are the averaged performance for each trial block.

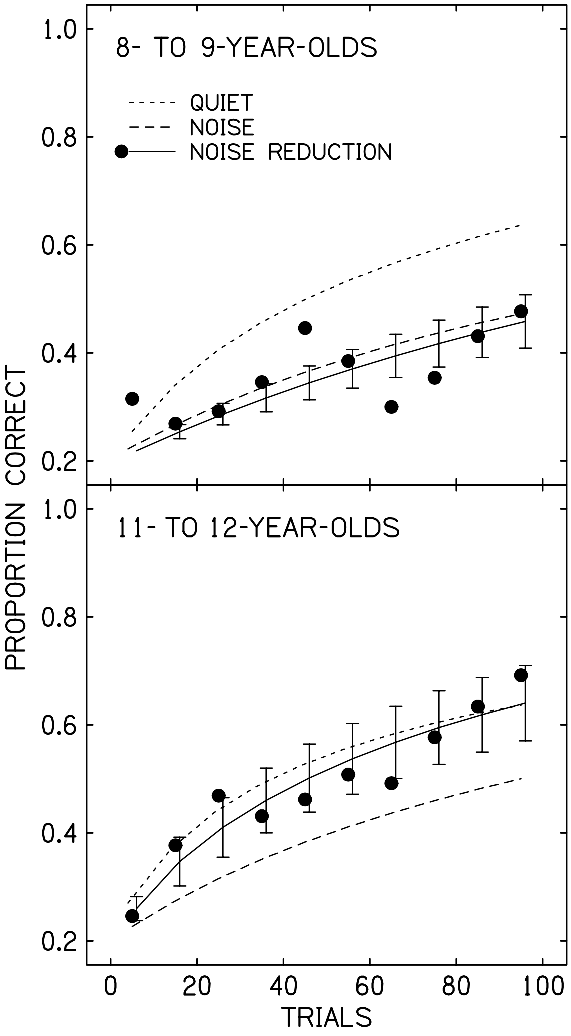


$\eta^2 = .116$, $\beta = .774$; and trial block, $F(1.157, 67.094) = 259.54, p < .001, \eta^2 = .817, \beta = 1.0$. Significant interactions were also observed for Listening Condition × Hearing Status, $F(1, 58) = 4.432, p = .040, \eta^2 = .071, \beta = .544$; Hearing Status × Trial Block, $F(1.157, 67.094) = 4.466, p = .033, \eta^2 = .071, \beta = .588$; and Listening Condition × Trial Block, $F(1.554, 90.120) = 4.997, p = .015, \eta^2 = .079, \beta = .727$. All other interactions were not significant.

These results indicate that, overall, performance improved significantly with each exposure to the words (main effect of trial block), the children with NH learned significantly faster than did the children with HL (main effect of hearing status), the older children learned faster than did the younger children (main effect of age group), and learning proceeded faster in quiet than in noise (main effect of listening condition). The significant Listening Condition × Hearing Status interaction indicates that the effects of noise and hearing loss combined to further reduce the performance of the children with HL relative to that of the children with NH.

The second goal of the present study was to determine the impact of DNR on word learning in children with HL. Figure 9 shows proportion correct as a function of trial for the children with HL using the same convention as that used in Figure 8, with the results of the noise reduction condition included. These results show that the performance of the younger children was the same

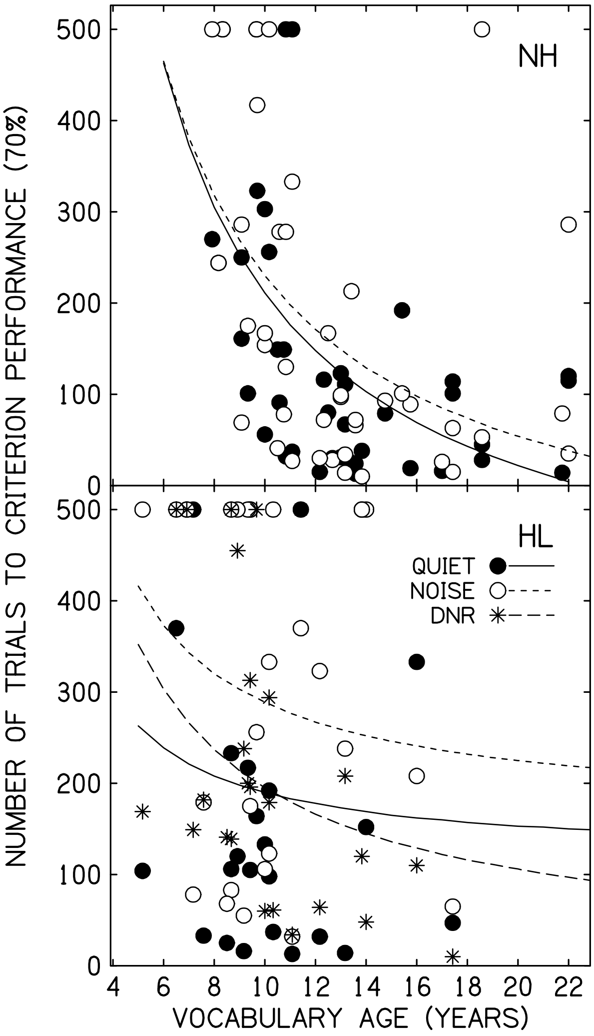
Figure 9. Averaged learning functions (±1 *SE*) for the two groups of children with HL—the 8- to 9-year-olds (upper panel) and the 11- to 12-year-olds (lower panel). Solid lines represent the learning function for the noise listening condition with DNR. Short and long dashed lines represent the quiet and noise listening conditions, respectively. Data points are the averaged performance for each trial block.



in noise with and without DNR, whereas the performance of the older children in noise improved with the use of DNR. Separate repeated measures ANOVAs were conducted for each age group to determine whether the learning functions for the noise and noise reduction listening conditions differed significantly. For both analyses, trial blocks and listening condition (noise, noise reduction) served as within-subjects factors. The analysis for the younger children revealed a significant main effect of trial block, $F(9.000, 12.091) = 28.182$, $p < .004$, $\eta^2 = .701$, $\beta = .998$, but not for listening condition, $F(1, 12) = 0.124$, $p = .731$, indicating that learning in noise was unaffected by DNR. For the older children, however, the analysis revealed significant main effects of both trial block, $F(9.00, 13.76) = 50.685$, $p < .001$, $\eta^2 = .809$, $\beta = 1.0$, and listening condition, $F(1, 12) = 4.881$, $p = .047$, $\eta^2 = .289$, $\beta = .528$, indicating that word learning in noise significantly improved with the use of DNR. These results suggest an age-related benefit of DNR for word learning in children with HL. Specifically, DNR had little effect on learning for children younger than 10 years but contributed significantly to word learning in children older than 10 years.

Because word learning is governed largely by a child's receptive vocabulary, the data were also examined as a function of their performance on the PPVT–III to better appreciate the effects of hearing status and listening condition. Recall that, in addition to fitting the children's data with a learning function, the analysis also provided an estimate of the number of trials needed to achieve 70% correct performance. Figure 10 shows the number of trials required by the children with NH (upper panel) and the children with HL (lower panel) as a function of vocabulary age. The parameter in each panel is listening condition. In this configuration, lower values indicate faster learning. Data points representing > 500 trials to criterion were truncated. Also note that the range of vocabulary ages differed across groups, with lower vocabulary ages for the children with HL. Regression functions for each listening condition are shown as solid and dashed lines. The results for the children with NH are consistent with a number of previous studies showing that word learning proceeds more rapidly as vocabulary knowledge increases. Also, the impact of noise on this group had little effect on their rate of word learning. The results for the children with HL show that their word-learning rate was more variable overall and decreased (more trials required) in noise relative to quiet. The use of DNR, however, improved word learning and somewhat restored the relation between age and vocabulary knowledge for these children. These data indicate that for children with mild to moderately severe HL, learning rate slowed when the acoustic signal was degraded by noise but improved to rates similar to those in quiet with the use of DNR.

Figure 10. Number of trials to criterion performance (70%) as a function of vocabulary age for the children with NH (upper panel) and the children with HL (lower panel). The parameter in each panel is listening condition. Regression functions are shown for each listening condition, indicating the relation between learning rate (lower is faster) and vocabulary age.



Factor Analysis

Although these results suggest that the age-related benefit observed with DNR may be due to the vocabulary knowledge of younger and older groups, other factors may have contributed to the children's performance as well, particularly given the heterogeneous characteristics of this group of children. Two factor analyses were performed to identify other characteristics that might predict which children with HL are more likely to benefit from DNR. For both analyses, Varimax rotations with Kaiser Normalization were performed, yielding two-factor solutions having Eigenvalues greater than 1. Within each solution, factor loadings greater than .80 were considered salient to the interpretation of each principal component. The resulting factor scores were correlated (Pearson's r) to the children's word-learning rate. The time constant c from Equation 1 was log-transformed and was used to represent the rate of word learning (recall that $1/c$ is equal to the number of trials required to reach criterion performance).

In the first analysis, seven variables representing different characteristics of the children with HL were entered: three variables associated with hearing history (age at identification of HL, age at amplification, and years of hearing aid use); overall SNR in noise without DNR; receptive vocabulary (PPVT–III age); hearing level of the right and left ears (average of 2 kHz, 4 kHz, and 8 kHz); and chronological age. The analysis reduced the data to three principal components, accounting for a total variance of 85%. The principal components were found to correspond to the children's hearing history (age of identification, age at amplification, and years of hearing aid use), which accounted for 44% of the variance; age (chronological and vocabulary age), which accounted for 28% of the variance; and overall SNR, which accounted for 13% of the variance. Pearson's r correlation coefficients revealed a significant relation between word-learning rate and age, $r = .354$, $p = .049$, but not for hearing history, $r = .249$, $p = .126$, or overall SNR, $r = –.241$, $p =.134$. The second analysis was the same as the first, with one exception—the overall SNR achieved with DNR was entered, and the overall SNR without DNR was removed. The analysis again reduced the data to three principal components, accounting for a total variance of 85%. The principal components were found to correspond to the children's hearing history (age of identification, age at amplification, and years of hearing aid use), which accounted for 44% of the variance; age (chronological and vocabulary age), which accounted for 27% of the variance; and overall SNR, which accounted for 15% of the variance. Pearson's r correlation coefficients again revealed a significant relation between word-learning rate and age, $r = .480$, $p = .020$, but not for hearing history, $r = .049$, $p = .837$, or overall SNR, $r = –.199$, $p = .361$. These results confirmed that although the children differed along a number of parameters, word learning in noise with and without DNR was significantly related to participants' chronological and vocabulary age.

Discussion

The purpose of the present study was to determine the rate of word learning in quiet and in noise for younger and older children with HL compared to their age-matched, NH peers. Of particular interest were the effects of DNR on word learning in noise for the children with HL. Performance for the multitrial, dynamic, word-learning task showed significant effects of age for the children with NH but not for the children with HL. Closer examination of the results revealed that, in quiet, the performance of the older children with NH was well above that of all other groups and that the performance of the remaining three groups was similar. That is, the learning rate across groups was the same with the exception of the older children with NH. These results are consistent with the vocabulary age of each group (see Figure 10). Vocabulary age was similar across groups with the exception of the higher vocabulary age of the older children with NH, who consequently learned the new words faster. These results are also in agreement with the factor analysis showing that learning rate was significantly related to vocabulary knowledge.

Conversely, significant effects of listening condition (quiet vs. noise) were observed for the children with HL but not for the children with NH. In noise, the performance of the children with NH was unchanged, whereas the performance of the children with HL decreased significantly. That is, more trials were required to learn the words presented in noise than in quiet. These results are consistent with the known effects of noise on amplification and on the perception of speech in noise by children with HL (Crandell, 1993). Therefore, these results may explain, in part, why the overall vocabulary knowledge of these children was poorer than that of their age-matched peers. Specifically, the acquisition of new vocabulary may be slowed in noise, reducing the value of each exposure to a new word. Over time, one would expect that the effect would become cumulative and would result in significantly reduced vocabulary knowledge for older children with HL. But this does not appear to be the case. What, then, keeps children with mild-to-moderate HL from continuing to lose ground in vocabulary development as they mature? One possibility is that children with HL are provided with—or seek out—additional exposures to a new word (e.g., verbal repetition, rehearsal, orthographic representation) in order to adopt that word into their vocabularies. These and other possibilities are areas for further research that may advance our understanding of the relation between hearing loss and critical auditory tasks such as word learning.

DNR

With the use of DNR, the performance of the younger children with HL was unchanged, whereas the performance of the older children improved significantly. Factor analyses confirmed that characteristics of HL in children (e.g., degree of HL, hearing history) did not contribute significantly to performance. Also, word learning was not related to the overall SNR of the stimuli in noise with or without DNR, which varied as much as 10 dB across children in each age group and for both noise conditions. One might expect that the children receiving a more favorable SNR would enjoy a faster word-learning rate, but this was not the case. Instead, word learning was, again, related to the vocabulary knowledge of the children.

Another possible contributor to the age-related benefits of DNR is that the older children with HL were better able to perceive the nonsense words in noise. A number of studies have shown that the speech perception of children with NH improves in noise with age (Elliott, 1979; Fallon, Trehub, & Schneider, 2002; Nozza, Rossman, Bond, & Miller, 1990; Scollie, 2008; Wilson, Farmer, Gandhi, Shelburne, & Weaver, 2010). Although the relation between age and speech perception in noise is less well defined for children with HL (Scollie, 2008; Stelmachowicz et al., 2007), age appears to be a strong predictor of performance (Gravel et al., 1999; Stelmachowicz, Pittman, Hoover, & Lewis, 2001). Even so, the effect of age was observed only when the children learned the words in noise when the DNR was activated. Perhaps the improvement in overall SNR (average of 2.3 dB), the reduction in overall stimulus level (average of 5.3 dB), and the older children's greater vocabulary knowledge provided the conditions necessary for the benefits of DNR to become apparent. If so, one might expect that the use of DNR for older and younger children with HL would increase the instances of tolerable noise levels and promote better word learning.

As for the younger children with HL, word learning did not improve with DNR, but it was not adversely affected, either. This result is consistent with other studies of DNR in children with HL (Auriemmo et al., 2009; Pittman, 2011; Stelmachowicz et al., 2010) and suggests that although DNR may not facilitate improved performance for auditory tasks in noise for this age group, performance is maintained. It is possible that these children may also benefit from increased listening comfort, although the long-term effect(s) of DNR on communication is a question for further research.

Implications of the Present Study

The results of this study suggest that DNR may provide amplification with which children can tolerate and learn in noise. This notion is supported by research showing that children with HL prefer amplification with more gain in quiet listening situations and less gain in louder, noisier listening conditions (Scollie et al., 2010). Without DNR, these preferences may be satisfied through the use of a volume control on the hearing aid or the use of multiple programs that differ in overall output. Although school-age children and adolescents are able to make appropriate volume control and programming selections (Scollie et al., 2010), younger children may not. The advantage of DNR is that it can be configured to automatically activate in the presence of noise, it requires little to no intervention by the child, and it maintains optimal amplification in quiet and in noise. Without DNR, the only recourse that a child may have against the aversive effects of noise is to remove the hearing aid(s) altogether.

Limitation of the Present Study

DNR systems differ substantially across makes and models of hearing aids. The results for the present study are based on one type of noise reduction at one SNR (0 dB) in one competitor (broadband noise). The benefits of DNR to word learning would likely differ under other presentation conditions and for other types of DNR. This places pediatric audiologists in a difficult position. They must rely on research regarding specific DNR processors that may be outdated due to the rapid development of new technologies and the time-consuming process of pediatric research. Instead, they may wish to refrain from using new technologies with children until sufficient evidence is available or when methods such as rapid word learning are developed for clinical use to verify the benefits of DNR and other forms of advanced signal processing.

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References

Akhtar, N. (2005). The robustness of learning through overhearing. *Developmental Science, 8,* 199–209.

Akhtar, N., Jipson, J., & Callanan, M. A. (2001). Learning words through overhearing. *Child Development, 72,* 416–430.

Alt, M. (2010). Phonological working memory impairments in children with specific language impairment: Where does the problem lie? *Journal of Communication Disorders, 44,* 173–185.

American National Standards Institute. (2004). Specifications for audiometers (ANSI S3.6-2004). New York, NY: Author.

Anglin, J. M., Miller, G. A., & Wakefield, P. C. (1993). Vocabulary development: A morphological analysis. *Monographs of the Society for Research in Child Development 58*(10, Serial No. 238).

Auriemmo, J., Kuk, F., Lau, C., Kelly-Dornan, B., Marshall, S., Pikora, M., . . . Sweeton, S. (2009). Efficacy of an adaptive directional microphone and a noise reduction system for school-aged children. *Journal of Educational Audiology, 15,* 15–27.

Bentler, R., & Chiou, L. K. (2006). Digital noise reduction: An overview. *Trends in Amplification, 10,* 67–82.

Bentler, R., Wu, Y. H., Kettel, J., & Hurtig, R. (2008). Digital noise reduction: Outcomes from laboratory and field studies. *International Journal of Audiology, 47,* 447–460.

Blamey, P. J., Sarant, J. Z., Paatsch, L. E., Barry, J. G., Bow, C. P., Wales, R. J., . . . Rattigan, K. (2001). Relationships among speech perception, production, language, hearing loss, and age in children with impaired hearing. *Journal of Speech, Language, and Hearing Research, 44,* 264–285.

Bloom, P. (2001). Fast mapping and the course of word learning. In P. Bloom (Ed.), *How children learn the meanings of words* (pp. 25–53). Cambridge, MA: The MIT Press.

Briscoe, J., Bishop, D. V., & Norbury, C. F. (2001). Phonological processing, language, and literacy: A comparison of children with mild-to-moderate sensorineural hearing loss and those with specific language impairment. *Journal of Child Psychology and Psychiatry, and Allied Disciplines, 42,* 329–340.

Chung, K. (2004). Challenges and recent developments in hearing aids. Part I. Speech understanding in noise, microphone technologies, and noise reduction algorithms. *Trends in Amplification, 8,* 83–124.

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

Delage, H., & Tuller, L. (2007). Language development and mild-to-moderate hearing loss: Does language normalize with age? *Journal of Speech, Language, and Hearing Reseach, 50,* 1300–1313.

Denes, P. B. (1963). On the statistics of spoken English. *The Journal of the Acoustical Society of America, 35,* 892–905.

Dollaghan, C. (1985). Child meets word: "Fast mapping" in preschool children. *Journal of Speech and Hearing Research, 28,* 449–454.

Dunn, L. M., & Dunn, L. M. (2006). *Peabody Picture Vocabulary Test—III*. Circle Pines, MN: AGS.

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. *The Journal of the Acoustical Society of America, 66,* 651–653.

Fallon, M., Trehub, S. E., & Schneider, B. A. (2002). Children's use of semantic cues in degraded listening environments. *The Journal of the Acoustical Society of America, 111,* 2242–2249.

Fellinger, J., Holzinger, D., Beitel, C., Laucht, M., & Goldberg, D. P. (2009). The impact of language skills on mental health in teenagers with hearing impairments. *Acta Psychiatrica Scandinavica, 120,* 153–159.

Gravel, J. S., Fausel, N., Liskow, C., & Chobot, J. (1999). Children's speech recognition in noise using omni-directional and dual-microphone hearing aid technology. *Ear and Hearing, 20,* 1–11.

Hansson, K., Forsberg, J., Lofqvist, A., Maki-Torkko, E., & Sahlen, B. (2004). Working memory and novel word learning in children with hearing impairment and children with specific language impairment. *International Journal of Language & Communication Disorders, 39,* 401–422.

Hoetink, A. E., Korossy, L., & Dreschler, W. A. (2009). Classification of steady state gain reduction produced by amplitude modulation based noise reduction in digital hearing aids. *International Journal of Audiology, 48,* 444–455.

Jerger, S., Martin, R., Pearson, D. A., & Dinh, T. (1995). Childhood hearing impairment: Auditory and linguistic interactions during multidimensional speech processing. *Journal of Speech and Hearing Research, 38,* 930–948.

Johnson, C. J., & Anglin, J. M. (1995). Qualitative developments in the content and form of children's definitions. *Journal of Speech and Hearing Research, 38,* 612–629.

Jutras, B., & Gagne, J. P. (1999). Auditory sequential organization among children with and without a hearing loss. *Journal of Speech, Language, and Hearing Research, 42,* 553–567.

Kiese-Himmel, C. (2008). Receptive (aural) vocabulary development in children with permanent bilateral sensorineural hearing impairment. *The Journal of Laryngology and Otology, 122,* 458–465.

Kochkin, S. (2002, October). MarkeTrak VI: 10-year customer satisfaction trends in the US hearing instrument market. *The Hearing Review, 9*(10), 14–25, 46.

Lederberg, A. R., Prezbindowski, A. K., & Spencer, P. E. (2000). Word-learning skills of deaf preschoolers: The development of novel mapping and rapid word-learning strategies. *Child Development, 71,* 1571–1585.

Lyxell, B., Andersson, U., Borg, E., & Ohlsson, I. S. (2003). Working-memory capacity and phonological processing in deafened adults and individuals with a severe hearing impairment. *International Journal of Audiology, 4*(Suppl. 1), S86–S89.

Mauchly, J. W. (1940). Significance test for sphericity of a normal *n*-variate distribution. *Annals of Mathematical Statistics, 11,* 204–209.

Mueller, H. G., Weber, J., & Hornsby, B. W. (2006). The effects of digital noise reduction on the acceptance of background noise. *Trends in Amplification, 10,* 83–93.

Nordrum, S., Erler, S., Garstecki, D., & Dhar, S. (2006). Comparison of performance on the hearing in noise test using directional microphones and digital noise reduction algorithms. *American Journal of Audiology, 15,* 81–91.

Nozza, R. J., Rossman, R. N., Bond, L. C., & Miller, S. L. (1990). Infant speech-sound discrimination in noise. *The Journal of the Acoustical Society of America, 87,* 339–350.

Peeters, H., Kuk, F., Lau, C. C., & Keenan, D. (2009). Subjective and objective evaluation of noise management algorithms. *Journal of the American Academy of Audiology, 20,* 89–98.

Pittman, A. L. (2008). Short-term word-learning rate in children with normal hearing and children with hearing loss in limited and extended high-frequency bandwidths. *Journal of Speech, Language, and Hearing Research, 51,* 785–797.

Pittman, A. (2011). Children's performance in complex listening conditions: Effects of hearing loss and digital noise reduction. *Journal of Speech, Language, and Hearing Research, 54,* 1224–1239.

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

Remez, R. E., Pardo, J. S., Piorkowski, R. L., & Rubin, P. E. (2001). On the bistability of sine wave analogues of speech. *Psychological Science, 12,* 24–29.

Rice, M. L., & Woodsmall, L. (1988). Lessons from television: Children's word learning when viewing. *Child Development, 59,* 420–429.

Ricketts, T. A., & Hornsby, B. W. (2005). Sound quality measures for speech in noise through a commercial hearing aid implementing digital noise reduction. *Journal of the American Academy of Audiology, 16,* 270–277.

Sarant, J. Z., Holt, C. M., Dowell, R. C., Rickards, F. W., & Blamey, P. J. (2008). Spoken language development in oral preschool children with permanent childhood deafness. *Journal of Deaf Studies and Deaf Education, 14,* 205–217.

Scollie, S. D. (2008). Children's speech recognition scores: The Speech Intelligibility Index and proficiency factors for age and hearing level. *Ear and Hearing, 29,* 543–556.

Scollie, S., Ching, T. Y., Seewald, R., Dillon, H., Britton, L., Steinberg, J., & Corcoran, J. (2010). Evaluation of the NAL-NL1 and DSL v4.1 prescriptions for children: Preference in real world use. *International Journal of Audiology, 49*(Suppl 1), S49–S63.

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

Scollie, S. D., Seewald, R. C., Moodie, K. S., & Dekok, K. (2000). Preferred listening levels of children who use hearing aids: Comparison to prescriptive targets. *Journal of the American Academy of Audiology, 11,* 230–238.

Seewald, R., Moodie, S., Scollie, S., & Bagatto, M. (2005). The DSL method for pediatric hearing instrument fitting: Historical perspective and current issues. *Trends in Amplification, 9,* 145–157.

Souza, P. E., Jenstad, L. M., & Boike, K. T. (2006). Measuring the acoustic effects of compression amplification on speech in noise. *The Journal of the Acoustical Society of America, 119,* 41–44.

Stelmachowicz, P. G., Lewis, D. E., Choi, S., & Hoover, B. (2007). Effect of stimulus bandwidth on auditory skills in normal-hearing and hearing-impaired children. *Ear and Hearing, 28,* 483–494.

Stelmachowicz, P., Lewis, D., Hoover, B., Nishi, K., McCreery, R., & Woods, W. (2010). Effects of digital noise reduction on speech perception for children with hearing loss. *Ear and Hearing, 31,* 345–355.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., & Lewis, D. E. (2001). Effect of stimulus bandwidth on the perception of /s/ in normal- and hearing-impaired children and adults. *The Journal of the Acoustical Society of America, 110,* 2183–2190.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., & Lewis, D. E. (2002). Aided perception of /s/ and /z/ by hearing-impaired children. *Ear and Hearing, 23,* 316–324.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., & Lewis, D. E. (2004). Novel-word learning in children with normal hearing and hearing loss. *Ear and Hearing, 25,* 47–56.

Storkel, H. L. (2001). Learning new words: Phonotactic probability in language development. *Journal of Speech, Language, and Hearing Research, 44,* 1321–1337.

Storkel, H. L. (2003). Learning new words. II: Phonotactic probability in verb learning. *Journal of Speech, Language, and Hearing Research, 46,* 1312–1323.

Storkel, H. L., & Lee, S. Y. (2011). The independent effects of phonotactic probability and neighborhood density on lexical acquisition by preschool children. *Language and Cognitive Processes, 26,* 101–211.

Vitevitch, M. S., & Luce, P. A. (2004). A web-based interface to calculate phonotactic probability for words and nonwords in English. *Behavioral Research Methods, Instruments, & Computers: A Journal of the Psychonomic Society, 36,* 481–487.

Vitevitch, M. S., Luce, P. A., Charles-Luce, J., & Kemmerer, D. (1997). Phonotactics and syllable stress: Implications for the processing of spoken nonsense words. *Language and Speech, 40*(Pt 1), 47–62.

Vitevitch, M. S., Luce, P. A., Pisoni, D. B., & Auer, E. T. (1999). Phonotactics, neighborhood activation, and lexical access for spoken words. *Brain and Language, 68,* 306–311.

Wake, M., Hughes, E. K., Poulakis, Z., Collins, C., & Rickards, F. W. (2004). Outcomes of children with mild-profound congenital hearing loss at 7 to 8 years: A population study. *Ear and Hearing, 25,* 1–8.

Walden, B. E., Prosek, R. A., & Worthington, D. W. (1975). *The prevalence of hearing loss within selected U.S. Army branches* (Final Report No. IAO 4745). Washington, DC: U.S. Army Medical Research and Development Command.

Wilson, R. H., Farmer, N. M., Gandhi, A., Shelburne, E., & Weaver, J. (2010). Normative data for the Words-in-Noise Test for 6- to 12-year-old children. *Journal of Speech, Language, and Hearing Research, 53,* 1111–1121.

Zekveld, A. A., Deijen, J. B., Goverts, S. T., & Kramer, S. E. (2007). The relationship between nonverbal cognitive functions and hearing loss. *Journal of Speech, Language, and Hearing Research, 50,* 74–82.

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