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# Short-Term Word-Learning Rate in Children With Normal Hearing and Children With Hearing Loss in Limited and Extended High-Frequency Bandwidths

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**Purpose:** This study examined children's word learning in limited and extended high-frequency bandwidth conditions. These conditions represent typical listening environments for children with hearing loss (HL) and children with normal hearing (NH), respectively.

**Method:** Thirty-six children with NH and 14 children with moderate-to-severe HL served as participants. All of the children were between 8 and 10 years of age and were assigned to either the limited or the extended bandwidth conditions. Five nonsense words were paired with 5 novel pictures. Word learning was assessed in a single session, multitrial, learning paradigm lasting approximately 15 min. Learning rate was defined as the number of exposures necessary to achieve 70% correct performance.

**Results:** Analysis of variance revealed a significant main effect for bandwidth but not for group. A Bandwidth  $\times$  Group interaction was also not observed. In this short-term learning paradigm, the children in both groups required 3 times as many exposures to learn each new word in the limited bandwidth condition compared with the extended bandwidth condition.

**Conclusion:** These results suggest that children with HL may benefit from extended high-frequency amplification when learning new words and for other long-term auditory processes.

**KEY WORDS:** word learning, children, normal hearing, hearing loss, bandwidth

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It is estimated that by the time a child graduates from high school, he or she will have acquired an understanding of more than 60,000 words. To achieve a vocabulary of this size, the child must learn multiple words per day throughout childhood (see Bloom, 2000, for a review). The immediate benefits of a well-developed vocabulary allow a child to learn to read comprehensively, write meaningfully, and speak effectively. The long-term benefits are apparent in the child's ability to communicate, socialize, and achieve academically and vocationally. Unfortunately, vocabulary development in children with hearing loss (HL) is often delayed and appears to be related to the child's degree of HL (Blamey et al., 2001; Boothroyd & Boothroyd-Turner, 2002; Davis, Efenbein, Schum, & Bentler, 1986; Lederberg, Prezbindowski, & Spencer, 2000; Pittman, Lewis, Hoover, & Stelmachowicz, 2005). Although children with language impairment (LI) also share similarly underdeveloped vocabularies, the underlying cause

may differ from that of children with HL. Specifically, children with LI may employ inefficient word-learning strategies, whereas children with HL may have difficulty learning new words because of a degraded auditory signal.

These two groups also experience difficulty with phonological processing, which may be related to their ability to learn new words (Briscoe, Bishop, & Norbury, 2001; Hansson, Forsberg, Lofqvist, Maki-Torkko, & Sahlen, 2004). Briscoe et al. (2001) compared the phonological, language, and literacy skills of 5- to 10-year-old children with HL with those of children with normal hearing (NH) and with children with LI. Their intent was to characterize the language skills of these children and to determine the impact of phonological processing difficulties on those skills. Their results revealed a significant relation between phonological processing and language in children with LI but not in children with HL. Specifically, the children with LI performed at levels significantly below that of their age- and vocabulary-matched peers on all but one measure (nonverbal reasoning). The children with HL, on the other hand, performed as well as the typically developing children on measures of nonverbal reasoning, receptive vocabulary, grammar, working memory, literacy, and digit span. The only exception was for children with greater HLs who were found to have poorer phonological skills than the normally hearing, typically developing children. When the language and literacy skills of these children were evaluated, the only significant effect of phonological impairment appeared to involve vocabulary knowledge. The authors concluded that poor phonological skills in children with HL are not necessarily associated with comprehensive LI but may have an impact on word learning.

To better understand the association between phonological processing and word learning, Gilbertson and Kamhi (1995) examined word learning in 20 children with HL between the ages of 7 and 10 years relative to children with NH who were matched for receptive language. They theorized that word learning in children with HL is related more to their ability to encode, store, and retrieve phonemic information than to the level of residual hearing. Four nonsense words differing in phonemic content and syllable length (tam, jaften, gadakik, and shabiffidy) were presented orally to each child and paired with a specific novel object. The child's ability to recognize, produce, and retain each word was measured. In addition, the child's performance on a number of phonological processing tasks (i.e., word repetition, rapid labeling) was measured. The children with HL wore their personal amplification devices (e.g., hearing aids, FM systems) during testing. The results revealed no significant differences between the groups for any of the phonological processing tasks or for recognition of the nonsense words. However, the children with HL required significantly

more repetitions of the nonsense words "jaften" and "shabiffidy" to produce them accurately. Further, analyses revealed a bimodal distribution in which half of the children with HL required significantly more repetitions of the nonsense words than the children with NH, whereas half did not. From this, the authors concluded that some children with HL may have significant LI that may be obscured and possibly complicated by the presence of HL.

However, studies (such as those described above) often do not control for the quality of the signal received by the children with HL. Instead, they rely on the child's personal amplification devices (hearing aids) or FM systems to provide an adequate speech signal during testing. Because phonological tasks, such as those used in Briscoe et al.'s (2001) and Gilbertson and Kamhi's (1995) studies, depend heavily on the child's ability to perceive the full acoustic content of the speech signal, it is possible that limitations in the children's personal hearing aids contributed to the phonological problems demonstrated by these children. For example, the children with HL in Gilbertson and Kamhi's study may have required more exposures to the nonsense words "jaften" and "shabiffidy" because hearing aids do not amplify the high-frequency fricatives well. Instead, the children may have required repeated attempts to produce these nonsense words as they searched for the correct acoustic phonetic content.

The effective bandwidth of most commercially available hearing aids is approximately 0.3–5.0 kHz, which is comparable with the bandwidth of a home telephone. It is often the case that proper names or unfamiliar terms must be spelled out over the telephone because of the ambiguity imposed by the restricted bandwidth. Also, the letters of an unfamiliar name or term are often associated with common names to avoid confusion with other letters having the same acoustic characteristics (e.g., T as in Tom, F as in Frank). Adult listeners appear to tolerate well the reduced spectral information provided by the telephone (and hearing aids) probably because very little information is new to them. Children, on the other hand, are bombarded with new information throughout childhood and into adolescence. Therefore, an ambiguous signal provided by hearing aids may reduce their ability to perceive speech as accurately as adults or their peers with normal hearing.

Several studies in children confirm the value of high-frequency information for perception, production, and clarity of speech. Stelmachowicz, Pittman, Hoover, and Lewis (2001, 2002) studied perception of the phoneme /s/ as a function of bandwidth. They reported systematic improvements in the performance of children with NH and children with HL as the bandwidth of the signal increased up to the 9-kHz bandwidth limit of the test protocol. In a later study, these investigators reported a distinct delay in the production of fricatives in a group

of young children with HL who were aided within the 1st year of life compared with their peers with normal hearing (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). Because the delay was restricted to the fricative class only, the authors theorized that the children received an ambiguous representation of fricatives via the limited bandwidth of their hearing aids. That is, the limited bandwidth made fricatives difficult to distinguish from one another. This notion is supported by the results of Kortekaas and Stelmachowicz (2000), who reported that 5- to 10-year-old children with NH required a wider bandwidth than adults to rate the phoneme /s/ as being clear. The results of these studies suggest that, unlike adults, children benefit from extended frequency bandwidths regardless of hearing status.

Although the immediate effect of a reduced bandwidth appears to be limited to the perception and production of certain phonemes (fricatives), it is important to recall that speech perception and production are only part of a child's communication development. Over the long term, children use these skills to increase their knowledge and understanding of the world. That is, whereas adults use their hearing to continue to communicate, children use their hearing to learn to communicate. Therefore, the value of an extended high-frequency bandwidth may be equally important for long-term auditory processes, such as word learning, that promote the development of communication.

## Word Learning

Experimental paradigms for word learning typically include a period in which the child is introduced to new words through direct labeling or indirectly in the form of a story or reference. Lederberg et al. (2000) have distinguished these two types of word-learning paradigms as either rapid word learning (i.e., fast mapping), in which the child is given an explicit reference for the new word, or novel mapping (i.e., quick incidental learning), in which the child is expected to make the connection between the new word and the unfamiliar object without assistance. In either paradigm, the words may be real, but unknown to the child, or nonsense words with a specific phonemic content. After a predetermined number of exposures, the child is tested to determine the degree to which he/she was able to learn the new words under the conditions imposed in the experiment. Although these paradigms may not represent exactly the process by which children learn words in their natural environment, they provide valuable information about factors that may affect word learning. To date, several factors have been identified and include age, receptive vocabulary, working memory, hearing level, number of exposures,

phonemic awareness, phonotactic probability,<sup>1</sup> and others (Gilbertson & Kamhi, 1995; Hansson et al., 2004; Lederberg et al., 2000; Oetting, Rice, & Swank, 1995; Pittman et al., 2005; Rice, Buhr, & Nemeth, 1990; Rice, Oetting, Marquis, Bode, & Pae, 1994; Stelmachowicz, Pittman, Hoover, & Lewis, 2004). Although all of these factors are accounted for in the present study, the effects of phonemic awareness, current receptive vocabulary, and hearing level are particularly relevant.

Storkel (2001, 2003) demonstrated the importance of the acoustic phonetic content of novel words when she investigated word learning in 3- to 6-year-old children. She carefully controlled the phonemic content of the novel words (nouns and verbs) so that the influence of phonotactic probability could be determined. The results suggested that the children's ability to learn words was influenced more by the acoustic-phonetic content of the word than by the grammatical function of the word. In addition, word learning was greater for words containing more commonly occurring phonemes. Because the acoustic-phonetic content of a word has a strong effect on learning, it is possible that a reduced bandwidth may affect the perception of phonemes and, therefore, learning.

Stelmachowicz, Pittman, Hoover, Lewis, and Moeller (2004) examined word learning in children with NH and children with HL as a function of presentation level. The children were between the ages of 6 and 9 years. They reported a positive relation between presentation level and word learning in both groups. That is, significantly more words were learned at higher presentation levels. Pittman et al. (2005) examined word learning in children with NH and children with HL as a function of stimulus bandwidth. In that study, the children were between the ages of 5 and 14 years. The bandwidth of the stimuli approximated the frequency response of a typical ear-level hearing aid appropriate for children (4 kHz) as well as a wider bandwidth that more closely approximated the range of normal human hearing (9 kHz). The children were exposed to eight CVCVC novel words a total of six times each in a single session before their retention was tested. Each novel word contained three unique phonemes in the same vowel context. Stelmachowicz, Lewis, Choi, and Hoover (2007) conducted a similar study of word learning in noise. Their participants were 7- to 14-year-old children with NH and with HL. They also presented six repetitions of eight novel words embedded in an animated story; however, the eight CVC words were composed of unique consonants and vowels and filtered to produce bandwidths of 5 and 10 kHz.

<sup>1</sup>Phonotactic 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).

The results of both studies showed no significant difference in word learning between the limited and extended bandwidth conditions. However, because the novel words in each study contained unique phonemes, the benefits of an extended high-frequency bandwidth may have been reduced in that perception of only one phoneme was necessary to identify any one word. The finite number of exposures to each word may have limited the evaluation of learning as well. A longitudinal, rather than a cross-sectional, approach may better inform our understanding of word learning and may be more sensitive to the effects of some amplification characteristics. That is, more may be learned by determining the number of exposures necessary to learn a new word in a short period of time rather than evaluating performance after a predetermined number of exposures. This may be particularly informative for language processes that develop over extended periods of time and for subtle amplification characteristics that may have significant cumulative effects.

In the present study, the acoustic phonetic content of the stimuli and the presentation parameters were carefully controlled to avoid variations in amplification that might arise from using the children's personal hearing aids. Also, a dynamic word-learning paradigm was used to determine the number of exposures required to learn a new word in a short period of time (15 min). The purpose of the present study was to determine the rate of word learning in children with NH and children with HL for words having frequency bandwidths that approximate typical hearing aids and that of normal human hearing. Rate of word learning was defined as the number of exposures necessary to achieve 70% correct performance in the multitrial paradigm. It was hypothesized that word learning would be significantly affected by the acoustic parameters of the physical signal in both groups of children.

## Method

### Participants

Thirty-six children with NH and 14 children with sensorineural HL served as participants. All children were between the ages of 8 and 10 years (mean NH = 9.6 years, *SD* = 0.9 months; mean HL = 9.3 years, *SD* = 0.9 months). Seven (50%) of the children with HL were boys as were 20 (56%) of the children with NH. A clinical audiometer was used to confirm the hearing status of the children with NH. Thresholds were <15 dB HL at octave frequencies between 0.25 and 4 kHz, <25 dB HL at 8 kHz, and <40 dB HL at 12 kHz. Table 1 shows the age, gender, and hearing thresholds for the left and right ears; age at identification; age at amplification; years of hearing aid use; and standardized vocabulary score for each child

with HL. The thresholds of the children with HL were measured using custom laboratory software (described below) and expressed in dB SPL. All of the children were oral and placed in mainstreamed classrooms with their age-matched peers. Each child wore hearing aids bilaterally, with the exception of 2 children who were not aided.

### Stimuli

Five CaCəC nonsense words were created and paired with five pictures of nonsense toys. The words were /saθnəd/, /daztəl/, /fasnəʃ/, /stamən/, and /hamtəl/. The vowels /a/ and /ə/ occurred in the first and second syllables of each word, respectively. Three repetitions of /t/, /s/, and /n/; two repetitions of /d/, /m/, and /l/; and one repetition of /ʃ/, /f/, /θ/, /z/, and /h/ were distributed across the five words. This distribution approximates the frequency with which these phonemes occur in spoken American English (Denes, 1963). Also, many of the consonant phonemes occurred in more than one word so that each child would be required to recognize and learn a combination of phonemes rather than relying on the intelligibility of just one of several unique phonemes in each word. Table 2 lists the orthographic representation of each word as well as the phonetic transcription and the phonotactic probability. Phonotactic probability was calculated using the procedure suggested by Vitevitch and Luce (2004). The first number listed (positional segment frequency) represents the likelihood of the phonemes occurring in their positions within the nonsense word as they may in real English words. The second number (biphone frequency) represents the likelihood that each pair of adjacent phonemes also occurs in English words. Higher values indicate that the phonemes occur frequently together or in a particular position. By design, these words were equated as closely as possible for phonotactic probability so that word learning would be independent of these effects.

Prior to testing, the nonsense words were presented orally to a class of 16 undergraduate students who were instructed to write an English word that sounded most like the nonsense word. The written responses were then tallied to determine whether a substantial number of the students associated any of the nonsense words with the same English word. No consistent responses were given for four of the five nonsense words, but half (8) of the students wrote the word "stamen" (the pollen-bearing part of a flower) for the word /stamən/. Coincidentally, the word "stamen" was an item in the vocabulary test administered to each child as part of the study protocol. Only 4 children recruited for the present study had vocabularies sufficient to reach that level of the test, and only 1 responded correctly. Therefore, the English word "stamen" was considered to be beyond the vocabularies

**Table 1.** Age, gender, hearing thresholds (in dB SPL) for the right and left ears; age at identification (Age ID); age at amplification (Aided); years of hearing aid use (HA use); and Peabody Picture Vocabulary Test (PPVT) standard score for each child with hearing loss.

Child number	Age (years: months)	Gender	Ear	Frequency (kHz)								Age ID (years)	Aided (years)	HA use (years:months)	PPVT standard score
				0.25	0.50	1	2	4	8	9	10				
Limited bandwidth condition															
1	9:0	Male	Right	73	65	77	83	73	92	80	83	2	2	7:0	98
			Left	72	68	78	75	70	97	83	93				
2	10:7	Male	Right	87	76	70	68	61	98	82	88	3	4	6:7	89
			Left	98	92	70	73	73	103	93	118				
3	8:1	Female	Right	83	75	79	87	78	98	63	84	2	3	5:1	95
			Left	87	58	97	89	61	67	58	72				
4	8:8	Female	Right	51	31	26	80	102	125	125	125	5	6	2:8	80
			Left	58	28	13	13	83	113	118	109				
5	9:11	Female	Right	33	25	43	73	88	113	102	123	5	6	3:11	113
			Left	23	27	44	63	98	110	94	99				
6	8:2	Male	Right	53	52	45	83	68	73	78	58	0	1	7:2	113
			Left	50	53	68	78	73	83	73	68				
7	8:2	Male	Right	47	38	38	43	28	63	78	78	0	2	6:2	102
			Left	48	33	48	42	33	63	73	72				
M	9:1		Right	61	52	54	74	71	95	87	91	2	3:5	5:5	99
			Left	62	51	60	62	70	91	85	90				
Extended bandwidth condition															
8	10:1	Female	Right	27	13	13	18	63	33	63	73	3			108
			Left	28	13	13	63	48	58	78	83				
9	9:8	Male	Right	69	98	97	72	68	46	48	53	0	2	7:8	84
			Left	61	72	68	86	76	67	36	43				
10	8:1	Female	Right	48	41	51	58	48	53	48	48	3	3	5:1	64
			Left	47	43	48	58	48	53	56	58				
11	9:6	Female	Right	68	68	78	75	53	63	78	93	2	2	7:6	116
			Left	63	67	73	85	55	68	73	73				
12	10:5	Male	Right	30	28	28	63	58	63	58	55	5	5	5:5	109
			Left	38	33	43	60	68	83	72	68				
13	9:11	Female	Right	47	33	38	48	48	58	58	63				115
			Left	38	33	38	48	52	58	58	62				
14	9:10	Male	Right	103	93	93	88	68	65	58	72	3	3	6:10	68
			Left	108	93	95	88	78	73	83	83				
M	9:7		Right	56	53	57	60	58	54	59	65	3	3	6:9	95
			Left	55	51	54	70	61	66	65	67				

Note. Numbers in italics represent the mean values.

**Table 2.** Orthographic and phonetic transcriptions of the five novel words.

Word	Phonetic transcription	Phonotactic probability	
		Positional segment	Biphone
Sothnud	saθnəd	1.3347	1.0081
Doztul	daztəl	1.3425	1.0146
Fosnush	fasnəʃ	1.3345	1.0073
Stomun	stamən	1.3445	1.0455
Homtul	hamtəl	1.3594	1.0212

Note. Phonotactic probability (positional and biphone frequencies) are also provided.

of most of the children in the study (8- to 10-year-olds) and likely had little effect on their ability to learn the word /stamən/.

The words were recorded by a female talker with a typical American English dialect using a sampling rate of 22.05 kHz and a microphone with a flat frequency response to 10 kHz (AKG, C535EB). As in typical conversational English, the stress was placed on the initial syllable. The words were digitally isolated from the original recording using Adobe Audition (V1.5) and saved as separate wave files. The words were then low-pass filtered to create two stimulus conditions. In the first stimulus condition, the words were low-pass filtered at 4 kHz (with a rejection rate of 60 dB/octave), which approximates

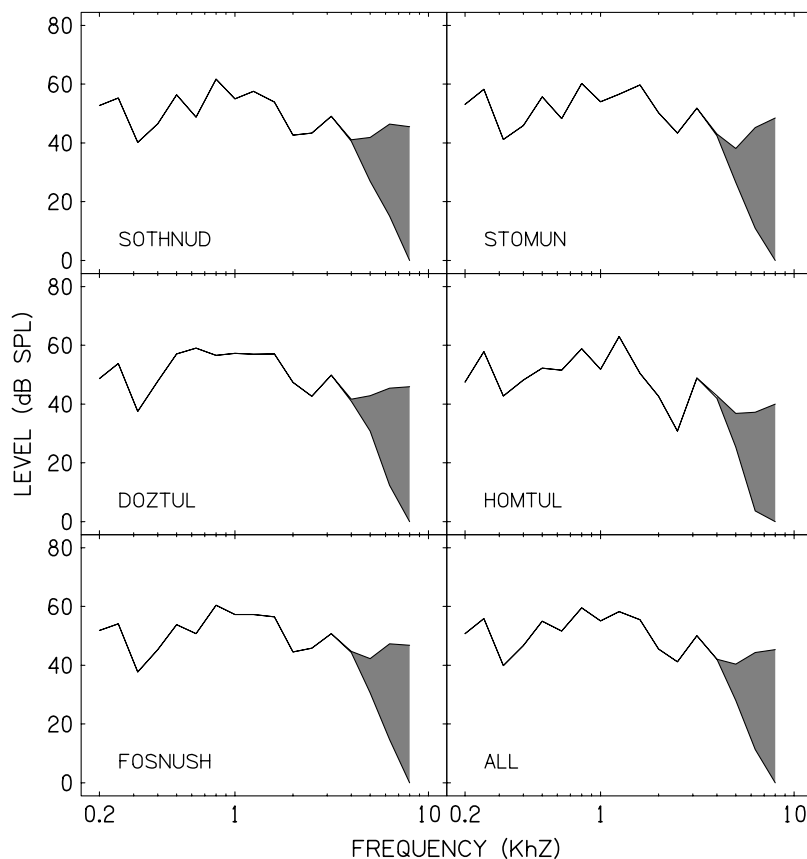
the bandwidth of currently available hearing aids appropriate for children (ear-level devices). For the second stimulus condition, the words were low-pass filtered at 9 kHz (with a rejection rate of 60 dB/octave), which approximates the frequency range of normal human hearing. Figure 1 shows the 1/3-octave band spectrum levels of each word as well as the average spectrum of all the words as presented to the children with NH. The shaded area in each panel represents the additional high-frequency amplitude provided in the extended bandwidth condition.

All stimuli were routed binaurally through earphones having a flat frequency response >10 kHz (Sennheiser, 25D). For the children with NH, the stimuli were presented at 65 dB SPL, which is consistent with average conversational speech. To accommodate the elevated thresholds of each child with HL, the stimuli were frequency shaped according to the target gain parameters provided by the desired sensation level (DSL) v4.1 fitting algorithm (Seewald et al., 1997). DSL does not provide targets for frequencies >6 kHz, so the targets at higher frequencies were estimated by comparing the level of the long-term average speech spectrum at adjacent

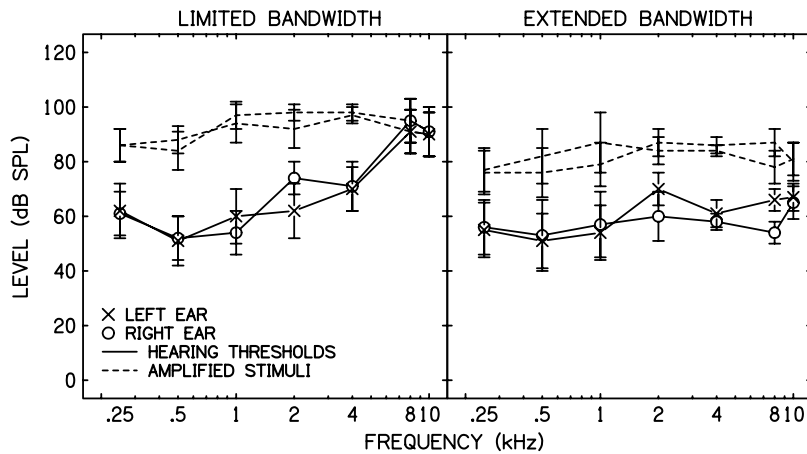
frequencies and then by providing similar amplification up to 15 dB of sensation at 9 kHz. Because the hearing thresholds and experimental results were obtained using the same equipment and calibration parameters, audibility of the stimuli was easily determined by referencing both to a 6-cm<sup>3</sup> coupler. Although real-ear dB SPL is ideal, standing waves in the ear canal make it difficult to determine the exact presentation levels at frequencies >4 kHz (Gilman & Dirks, 1986). Therefore, threshold and stimulus measures were referenced to a 6-cm<sup>3</sup> coupler to obtain relative estimates of sensation for each child.

Figure 2 shows the average hearing thresholds (+1 SE) for the right and left ears for the children with HL in the limited and extended bandwidth conditions (left and right panels, respectively). The average presentation levels of the stimuli are also shown. Note that the hearing levels of the children in the limited bandwidth condition are more severe in the high frequencies than for the children in the extended bandwidth condition. Although group assignment was random for most of the children with HL, those children with greater high-frequency losses at 9 kHz were placed in the limited

**Figure 1.** Third-octave spectrum levels for each word as well as the combined long-term spectrum (lower right panel) as presented to the children with normal hearing.



**Figure 2.** Average presentation levels (in dB SPL) as a function of frequency (kHz) for the children with hearing loss in the limited and extended bandwidth conditions (left and right panels, respectively). Average hearing thresholds for the right and left ears are also provided. Error bars represent  $\pm 1$  SE. All levels were referenced to a 6-cm<sup>3</sup> coupler.



bandwidth group because adequate sensation of the stimuli would have exceeded the output limits imposed in this study.

## Procedure

*Receptive vocabulary.* Prior to testing, the Peabody Picture Vocabulary Test—III (PPVT—III, Form B; Dunn & Dunn, 2006) was administered to determine each child's current receptive vocabulary. For this and the following test, the children with HL wore their personal hearing aids and were tested in a quiet room. The results of the PPVT were used to equate the receptive vocabularies of the children assigned to each listening condition (described below) because previous research suggests that word learning is related to the size of a child's current vocabulary. In this way, the influence of receptive vocabulary on word learning could be controlled a priori so that the effects of stimulus condition might be more apparent.

*Working memory.* The Rey Auditory-Verbal Learning Test (AVLT) was also administered to assess verbal memory and retention (Lezak, Howieson, & Loring, 2004; Taylor, 1959; van den Burg & Kingma, 1999). The test requires the child to learn and retain a list of familiar words read aloud. This test has been used extensively with both children and adults to determine the effects of various disorders, such as traumatic brain injury and degenerative diseases on working memory (e.g., multiple sclerosis, Alzheimer's, Huntington's). A list of 15 monosyllabic words familiar to children is read five times to the child at a rate of one word per second. After each repetition of the list, the child's task is to recall as many words

as possible in no particular order and in no predetermined period of time. The number of words recalled on each of the five repetitions of the list is then tallied and compared with normative values for typical children (van den Burg & Kingma, 1999). Although these data may be analyzed a number of ways (e.g., total words acquired, interference, number of repetitions, retention after delay), for purposes of this study, only the total number of words retained after each of the five recitations was calculated. The results of this test were used to identify any apparent differences between the children in the two stimulus conditions so that the effects of verbal learning and retention could be accounted for statistically.

*Word learning.* The children with NH and the children with HL were divided into two equal subgroups. Each subgroup learned the five words in the limited or the extended bandwidth condition, but not in both. Each child participated in two word-learning tasks: a familiarization task and a learning task. In the familiarization task, the child was briefly exposed to the visual pictures of toys and their names. A picture of a novel toy was displayed on a computer screen while the child heard, "This is a \_\_\_\_\_. Can you say \_\_\_\_\_?" The examiner then listened to the child's production to confirm that he/she produced the word correctly before moving on to the next picture. The familiarization task consisted of three repetitions of each word (two aural presentations and one production by the child). This task was similar to fast mapping in that the child was provided several directed exposures to the words and their associated toys before beginning the learning task.

In the learning task, the child played a simple computer game to learn the names of the five toys. Prior to

implementing the task, each child was given the following instructions by the examiner:

You will play a computer game to see how quickly you can learn the names of the toys. In the game you will see the pictures of the five toys on the computer screen. Then you'll hear a woman tell you a toy name. Select the toy that you think has that name. If you're right, the game will play. If you're not right, nothing will happen. At first you may not get very many right, but keep trying. As you play the game, you'll get better and better.

This task was similar to novel mapping in that the child was expected to connect the novel word to the correct novel object.

Custom laboratory software was used to randomly select a word, process it according to the frequency-shaping parameters calculated for each child, provide feedback in the form of a simple video game (e.g., dot-to-dot, puzzle), record the trial-by-trial data, and display real-time data analysis for the examiner. Figure 3 shows the interactive response screen used by the children for this task. A picture of each toy was displayed as response buttons on the left side of the computer screen. For each correct response, the video game on the right side of the screen was advanced incrementally (e.g., the next line was drawn in the dot-to-dot game). The video game did not advance for incorrect selections. The learning task consisted of a total of 150 trials (30 repetitions of each

word presented randomly) and took approximately 15 min to complete.

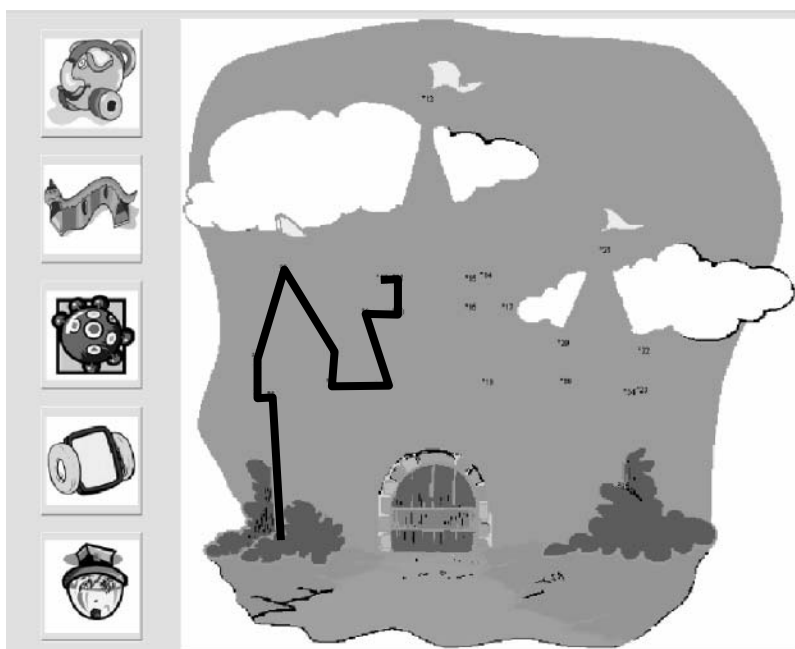
In the event that one toy-name association was more salient than the others or if one toy was simply more appealing, the name associated with each toy was rotated systematically for each child. That is, the toy-name association was different for each child. This reduced the effects of picture or word preference by distributing the effect across children. All testing was conducted in a sound-treated booth in the presence of an examiner who evaluated the child's production of the words, encouraged consistent attention to each task, and answered any questions that the child had.

## Results

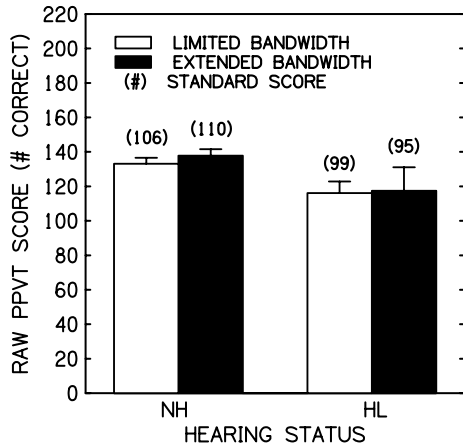
### Preliminary Tests

Figure 4 shows the average PPVT raw scores ( $\pm 1 SE$ ) as a function of group (NH and HL). The children enrolled in the limited and extended bandwidth conditions are indicated by open and filled bars, respectively. The average standard score for each group and condition is also indicated in parenthesis above each bar. The raw scores were subjected to a univariate analysis of variance with hearing status (NH, HL) and bandwidth (limited, extended) as between-subjects factors. A significant main effect of

**Figure 3.** Interactive response screen used by the children to select a toy after the presentation of each novel word. Feedback was provided via several video games. In this example, the dot-to-dot game was incrementally advanced after each correct response.



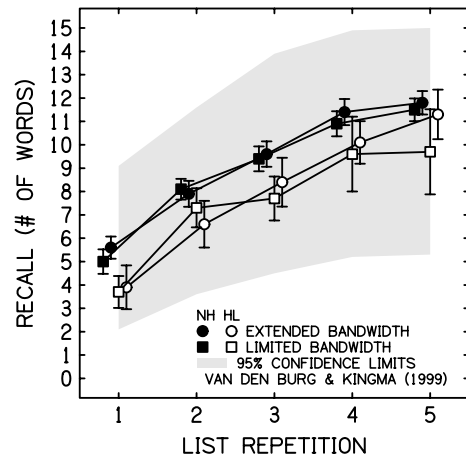
**Figure 4.** Average raw scores for the Peabody Picture Vocabulary Test (PPVT) as a function of hearing status (normal hearing [NH] and hearing loss [HL]). Error bars represent  $\pm 1$  SE. The children enrolled in the limited and extended bandwidth conditions are indicated by open and filled bars, respectively. Standard scores are shown in parentheses.



hearing status was revealed,  $F(1, 46) = 9.1, p < .01$ , but not for bandwidth,  $F(1, 46) = 0.2, p = .63$ . There was no Hearing Status  $\times$  Bandwidth interaction,  $F(1, 46) = 0.1, p = .79$ . These results indicate that across groups the children with NH had significantly higher receptive vocabularies, but within each group the children assigned to each bandwidth condition possessed similar vocabularies. Therefore, any difference between the word-learning rates of the children in each stimulus condition was not due to differences in receptive vocabulary.

Figure 5 shows the mean AVLT scores ( $\pm 1$  SE) as a function of list repetition for the children with NH (filled symbols) and the children with HL (open symbols). The children enrolled in the extended and limited bandwidth conditions are indicated by circles and squares, respectively. The symbols have been jittered slightly to expose the overlapping error bars. The shaded area represents the 95% confidence intervals for typical 8- to 10-year-old children (van den Burg & Kingma, 1999). Recall that the AVLT is a measure of verbal memory and retention of familiar words. The average performance of each group suggests a systematic increase in the number of words retained with each repetition of the list. The children with HL, however, retained consistently fewer words across repetitions than the children with NH. Even so, the children assigned to the two stimulus conditions within each group demonstrated similar learning functions suggesting that any difference between the word-learning rates across stimulus conditions was not due to differences in verbal memory and retention.

**Figure 5.** Average recall for the Rey Auditory-Verbal Learning Test as a function of list repetition. Error bars represent  $\pm 1$  SE. Children with NH and children with HL are represented by filled and open symbols, respectively. The children enrolled in the limited and extended bandwidth conditions are indicated by squares and circles, respectively. The shaded area represents the 95% confidence interval for typical 8- to 10-year-old children (van den Burg & Kingma, 1999).



## Word Learning

To characterize word learning, the data from the learning task were used to create growth functions for each of the four groups (2 hearing status  $\times$  2 bandwidth). The most efficient way to do this was to fit learning curves to the data and base any inferences on the parameter that characterized the curve. In this case, an exponential growth function was chosen and used the time constant of that function to indicate the number of exposures necessary to acquire new words. The exponential growth function is as follows:

$$P_L = 1 - e^{-n/c}, \quad (1)$$

where  $P_L$ , the probability of learning, ranges from 0 to 1;  $e$  is 2.718 ...;  $n$  is the number of the trial block; and  $c$  is the time-constant of the process. When the number of trials happens to equal the time constant,  $n = c$ , learning is almost two thirds complete ( $P_L = 0.63$ ); furthermore, when  $n = 3c$ , learning is 95% complete.

In this experiment, a child who could make no discrimination at all would be correct just one time out of five by chance. Therefore, the floor of the performance was not 0% correct but 20% correct. Thus, the model of learning, Equation 1, was corrected for chance to give a model of performance that could be used to map the data. The standard correction for guessing was used: The probability of being correct ( $P_C$ ) equals the probability of having learned ( $P_L$ ), plus the probability of not yet having

learned  $(1 - P_L)$ , times the probability of getting the answer by chance ( $P_{Ch}$ ):

$$P_C = P_L + (1 - P_L)P_{Ch}. \quad (2)$$

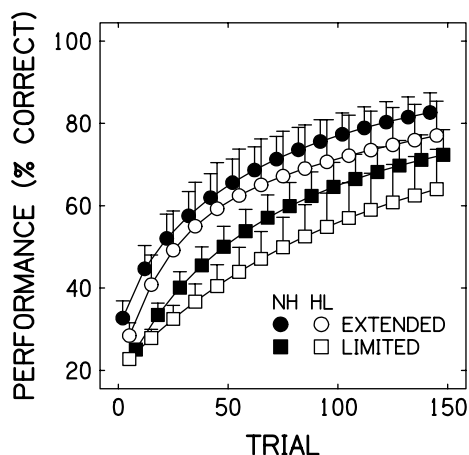
Putting this together with the learning model provided the predicted rate of improvement in performance:

$$P_C = 1 - 0.8e^{-n/c}, \quad (3)$$

where  $P_C$  is the probability of a correct answer, and, as before,  $n$  is the number of the trial block, and  $c$  is the time constant for the learning process. With this formula,  $P_C = 0.2$  when  $n = 0$ , with the curve growing from that raised floor in a smooth fashion to 1.0. When  $n = c$ , performance is approximately 70% (70.57%) correct.

The advantage of using Equation 3 to model the data was that all data points in the learning process contributed to the determination of the time constant. Because the speed of learning—the key dependent variable—is simply  $1/c$ , fitting Equation 3 to the data was the best way to address the experimental question. This was accomplished by adjusting estimates of  $c$  to minimize the sum of squared deviations between the data and the points predicted. Figure 6 shows the learning functions ( $+1 SE$ ) for each group and bandwidth condition averaged across children. Hearing status is indicated by filled and unfilled symbols, whereas bandwidth is indicated by circles and squares. The symbols have been jittered to expose the overlapping error bars. The slopes of the learning functions were greater for the children in the extended bandwidth condition as were the slopes for the children with NH. That is, the performance of the children in the

**Figure 6.** Averaged learning functions ( $+1 SE$ ) for the novel words as a function of trial number. Children with NH and children with HL are represented by filled and open symbols, respectively. The children enrolled in the limited and extended bandwidth conditions are indicated by squares and circles, respectively.



extended bandwidth condition exceeded that of the children in the limited bandwidth condition as did the performance of the children with NH relative to the children with HL. These results suggest that the extended bandwidth condition allowed both groups of children to learn the words more rapidly than in the limited bandwidth condition.

To determine whether the acoustic characteristics of the input affected the number of exposures necessary for the children to learn new words, the number of exposures necessary to reach a performance of 70% was estimated for each child using the harmonic mean of the blocked trials. The harmonic mean, rather than the arithmetic or geometric mean, was used because it is appropriate for calculating the average of rates. It more accurately describes the number of trials required for learning, and it tends to compensate for extreme outliers. The learning rates were then log transformed and subjected to a univariate analysis of variance with hearing status (NH, HL) and bandwidth (limited, extended) as between-subjects factors. A significant main effect of bandwidth condition was revealed,  $F(1, 46) = 5.8, p = .02$ , but not an effect of hearing status,  $F(1, 46) = 1.8, p = .19$ . There was also no Hearing Status  $\times$  Bandwidth interaction,  $F(1, 46) = 0.6, p = .44$ . These results indicate that on average, the children required fewer exposures to learn the words in the extended bandwidth condition regardless of hearing status.

Two additional analyses were conducted to address directly the primary question of interest. That is, did the word-learning rate of each group increase in the extended bandwidth condition? A one-tailed  $t$  test was used to compare the learning rates of the children with NH in each bandwidth condition. The results reveal a significant difference between the bandwidth conditions,  $t(34) = 1.8, p = .04, d = 0.75$ , and suggest that these children required significantly fewer exposures to learn the new words in the extended bandwidth. The effect size indicates that on average, the rate of word learning by the children in the extended bandwidth exceeded that of the children in the limited bandwidth condition by 0.75 standard deviations. An additional one-tailed  $t$  test was conducted to compare the learning rates of the children with HL as a function of bandwidth. No significant difference between the learning rates in each bandwidth condition was revealed,  $t(12) = 1.4, p = .10$ . Although the learning functions for these children suggest a large effect of bandwidth (see Figure 6), the lack of significance is likely due to the smaller number of children in this group.

### Number of Exposures Required for Learning

On average, the children with NH required 20 trials to achieve the criterion performance level (70%) in the

extended bandwidth condition, whereas 72 trials were necessary in the limited bandwidth condition. For the children with HL, 43 trials were necessary to achieve the criterion performance in the extended bandwidth condition, whereas 121 trials were necessary in the limited bandwidth condition. For easier interpretation, the learning rate for a single word in these conditions was also calculated using the same criterion performance (70%). On average, the children with NH required 5 trials to learn each word in the extended bandwidth condition, whereas 16 trials were required in the limited bandwidth condition. The children with HL required 10 trials to learn each word in the extended bandwidth condition, whereas 27 trials were necessary in the limited bandwidth condition. The results suggest that compared with the children with NH, the children with HL required approximately twice the number of exposures to learn each word. Also, although the group effect was not statistically significant for the children with HL, both groups required 3 times as many trials to learn the new words in the limited bandwidth condition.

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## Discussion

The purpose of the present study was to determine the short-term word-learning rate of children as a function of their hearing status and the bandwidth of the speech signal. It was hypothesized that word learning would be significantly affected by the acoustic parameters of the physical signal. The principle result from this study suggests that regardless of hearing status, the children learned words significantly faster (fewer exposures were necessary) when they were provided with a speech signal that encompassed a bandwidth similar to that of NH. Conversely, the children learned words more slowly (more exposures were necessary) when they were provided with a limited speech signal.

These results are consistent with the results of studies showing that children with HL possess significantly smaller vocabularies than children with NH and may explain, in part, why they are unable to learn words as well as their peers with normal hearing (Briscoe et al., 2001; Gilbertson & Kamhi, 1995; Hansson et al., 2004). That is, the amplified signal provided to children with HL may be insufficient to promote optimal word learning. These results also suggest that the phonological difficulties demonstrated by children with HL may be associated with the somewhat ambiguous signal that they receive through their hearing aids. Because word learning requires a child to perceive the subtle acoustic elements of the word to distinguish it from other similar words, they may require more exposures to overcome the ambiguous signal that they receive. That ambiguity also may be responsible, in part, for the poorer performance

demonstrated by children with HL on phonological processing tasks (Briscoe et al., 2001; Hansson et al., 2004) and would suggest that some speech and language measures are sensitive to variations in the integrity of the acoustic signal. For example, a common test of phonological processing requires that the child repeat aloud nonsense words that increase in syllable length. It is not difficult to imagine that a child receiving a limited acoustic signal would find it difficult to repeat the word, much like trying to perceive an unfamiliar name or term over the telephone.

Recall that the qualitative difference between the limited and extended bandwidth conditions is quite subtle, particularly when perceiving familiar speech. The results of this study suggest that the qualitative contributions of high-frequency energy to speech perception may be quantitative over the long term for children who are listening to and learning unfamiliar speech. In addition to the subtle effects of high-frequency amplification, it is possible that other amplification characteristics (e.g., frequency compression, noise reduction, directional microphones) also may interact with word learning in children with HL. To date, no studies are available regarding the effect of these amplification characteristics on word learning. The consistent difference, and in some studies the increasing difference, between the receptive vocabularies of children with HL and age-matched children with NH (Blamey et al., 2001; Pittman et al., 2005) suggests an urgent need to determine those amplification parameters that provide a comprehensive acoustic signal so that word learning may be optimized in children with HL.

## *Limitations of the Current Study*

It is important to recognize the limitations of the short-term paradigm used in the present study as well as the results of that paradigm. First, the controlled conditions necessary to examine an acoustic effect (e.g., sound treated room, high-fidelity earphones) limit the generalization of the results because the test conditions are far from most naturalistic learning environments. It is possible that the benefits of an extended bandwidth may be enhanced or reduced by such things as speech reading, contextual cues, background noise, and distance from the talker. Second, and most important, the number of exposures necessary to learn the words in this short-term paradigm should not be interpreted as the number of exposures that a child may require over a more extended period of time or under different circumstances. Instead, they should be interpreted in relative terms and in the context of the acoustic parameters under examination.

Finally, it is important to recall that children with HL are a highly heterogeneous population. In addition to

the factors that contribute to the variability of all children (e.g., age, IQ), children with HL also vary in terms of the etiology of the HL; the degree and configuration of the HL; the age at which they were identified and provided with intervention; the hearing aid make, model, and features prescribed to them; their mode of communication; the consistency with which they use their hearing aids or attend intervention programs; and the support that they receive from their parents and other family members. Not only do these factors make it difficult to recruit a homogenous group of children for research but the application of the results to this population is even more questionable. It is likely that each child with HL requires a unique intervention plan to optimize his or her auditory processing. However, because some direction regarding the best course of action is helpful, children with NH are also examined (as was done in the present study) to confirm the benefits of a particular form of intervention in the absence of the factors that can confound the performance of children with HL.

### Future Directions for Research

The results of the present study suggest that subtle variations in the acoustic signal may affect long-term auditory processes in children. Although extending the bandwidth of a signal is perceived as an increase in sound quality (Munro & Lutman, 2005; Versfeld, Festen, & Houtgast, 1999), that increased quality appears to have a quantitative effect in children who use their hearing primarily to learn. More research is needed to determine the extent to which other seemingly subtle properties of the amplified signal affect long-term auditory processes in children. For example, noise-reduction algorithms may have negligible effects on speech recognition thresholds (Alcantara, Moore, Kuhnel, & Launer, 2003) but may have a significant cumulative effect on long-term processes, such as word learning (Marcoux, Yathiraj, Cote, & Logan, 2006). Likewise, frequency transposition may not improve speech perception significantly in the short term (McDermott & Dean, 2000; McDermott, Dorkos, Dean, & Ching, 1999; McDermott & Knight, 2001) but may improve word learning over time. The learning paradigm employed in the present study may be a useful tool for tapping into the word-learning process to evaluate the effect of these and other amplification characteristics.

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