Research Article

Vocabulary Facilitates Speech Perception in Children With Hearing Aids

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Purpose: We examined the effects of vocabulary, lexical characteristics (age of acquisition and phonotactic probability), and auditory access (aided audibility and daily hearing aid [HA] use) on speech perception skills in children with HAs.

Method: Participants included 24 children with HAs and 25 children with normal hearing (NH), ages 5–12 years. Groups were matched on age, expressive and receptive vocabulary, articulation, and nonverbal working memory. Participants repeated monosyllabic words and nonwords in noise. Stimuli varied on age of acquisition, lexical frequency, and phonotactic probability. Performance in each condition was measured by the signal-to-noise ratio at which the child could accurately repeat 50% of the stimuli.

Results: Children from both groups with larger vocabularies showed better performance than children with smaller vocabularies on nonwords and late-acquired words but not early-acquired words. Overall, children with HAs showed poorer performance than children with NH. Auditory access was not associated with speech perception for the children with HAs.

Conclusions: Children with HAs show deficits in sensitivity to phonological structure but appear to take advantage of vocabulary skills to support speech perception in the same way as children with NH. Further investigation is needed to understand the causes of the gap that exists between the overall speech perception abilities of children with HAs and children with NH.

Speech perception, or the ability to accurately perceive and encode information in a speech signal, is a basic requirement for vocabulary development in all children, including children who wear hearing aids (HAs). Relative to children with normal hearing (NH), children with HAs generally show poorer speech perception performance on word recognition tasks (Stiles, Bentler, & McGregor, 2012), particularly in adverse listening conditions, such as high reverberation (Finitzo-Hieber & Tillman, 1978). A number of factors have been shown to be associated with better speech perception in children with HAs, including higher aided audibility (McCreery et al., 2015; Scollie, 2008; Stelmachowicz, Hoover, Lewis, Kortekaas, & Pittman, 2000), older age (Stelmachowicz et al., 2000), and milder degree of hearing loss (Blamey et al., 2001). In addition, a

complex bidirectional association between speech perception and vocabulary likely exists, but the effect of vocabulary on the speech perception of children with HAs remains unclear. Some studies have shown that a large vocabulary aids speech perception (Blamey et al., 2001; McCreery et al., 2015), while others have shown no effect of vocabulary in children with HAs (Stelmachowicz, Pittman, Hoover, & Lewis, 2004). Vocabulary size may selectively facilitate the perception of stimuli with particular characteristics, such as nonwords or late-acquired words, and this effect may not be apparent under all speech perception conditions. Despite the extensive body of research that has examined speech perception outcomes of children with HAs, little is known about the underlying perceptual processes that facilitate speech perception in children with HAs. The primary goal of this study was to examine the effect of vocabulary on the speech perception of children with HAs to better understand the mechanisms that drive speech perception in these children.

Lexical Restructuring in Children with NH

The development of speech perception has been more thoroughly studied in children with NH than children with HAs. One theory that addresses the developmental changes of speech perception and language learning is the concept of lexical restructuring, which has received widespread

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support (e.g., Charles-Luce & Luce, 1995; Metsala, 1997; Storkel, 2002; Ventura, Kolinsky, Fernandes, Querido, & Morais, 2007; Walley, Metsala, & Garlock, 2003). According to this theory, early word recognition is based on a holistic approach in which word representations are stored at the lexical level and include little within-word phonological detail that can be used for word recognition (Aslin & Smith, 1988; Walley, 1993). As vocabulary grows, the child's lexicon becomes increasingly crowded so that holistic analysis of spoken words becomes less efficient. To distinguish the mental representations of perceptually similar words, the child develops a more fine-grained level of analysis that is sensitive to the phonological structure within words. Vocabulary growth propels the development of a more mature perceptual system that children use to segment words on the basis of phonological structure. At the conclusion of this lexical restructuring, the child is fully sensitive to word-internal phonological structure and can make use of this fine-grained information during word recognition. This information is also included in the mental word representations. This shift from a more holistic to a phonologically detailed approach to speech perception occurs gradually over time so that a given phonological representation may become increasingly more fine-grained (Metsala, 1997; Walley, 1993). This shift also occurs gradually across words so that the level of detail afforded to representations may differ from word to word. Words previously stored as holistic representations may also be reanalyzed to include more phonological details than originally included in the representations.

The shift from holistic to fine-grained processing of speech likely is driven by a change in the perceptual weight that the child applies to different aspects of the speech signal. As the need to distinguish between phonologically similar words increases, the child puts more weight on the phonological structure within a word relative to the information available at the syllabic or lexical level (Nittrouer, 1996; Nittrouer & Lowenstein, 2007). Thus, the child can perceive fine-grained phonological structure within words from an early age, but only with increased language experience and a growing mental lexicon can the child learn to pay attention to this information during word recognition. When listening to ongoing speech, sensitivity to the phonological structure within words allows for more accurate word recognition in the presence of a degraded speech signal with missing acoustic-phonetic information (Metsala, 1997).

Past studies provide evidence for the hypothesis that word representations begin at a holistic level (Bertoncini, Bijeljac-Babic, Kennedy, Jusczyk, & Mehler, 1988). For example, Stager and Werker (1997) examined the ability of 14-month-old infants to perceive and make use of fine phonological information in a series of speech perception and word-object association tasks. They found that 14-month-old infants were able to distinguish between two different word-object pairings only when the two nonsense labels were phonologically dissimilar. When the labels were phonologically similar, the infants did not show evidence of discriminating

between the two labels. However, in a speech perception task that did not require word-to-object matching, the infants could distinguish the phonologically similar labels. Thus, although infants are able to discriminate between speech stimuli at the phonological level even during the first year of life, they may not pay attention to or otherwise make use of these phonological details when developing representations of words until a later age.

The findings of Metsala (1997) support the idea that robust, phonologically fine-grained word representations develop over time and with linguistic experience and that this segmental restructuring is driven by the need to discriminate words from other phonologically similar words. Metsala (1997) used a gating task with 7-, 9-, and 11-year-old children and adults and found that performance between these groups was the most similar for high-frequency words from dense lexical neighborhoods. Words from dense neighborhoods require the most robust phonological representations because they must be distinguished from a large number of competitors. Moreover, younger children have more opportunities to develop robust representations for high-frequency than low-frequency words due to frequent exposure to these words. This finding supports the idea that robust, fine-grained representations of words develop over time after increased experience with the words, and the words that are most likely to undergo this process of segmental restructuring are those that most need to be distinguished from many phonologically similar words. Also, adults and older children in this study showed better performance than younger children on words from sparse neighborhoods and low-frequency words, all of which should have been within the lexicon of the younger children. These words are likely the last to develop fine-grained phonological representations, which explains the developmental effect of recognition of these words in the gating task. Adults and older children required less phonological information about the target words because they had developed robust representations of these words, whereas younger children used more holistic representations of these low-frequency and sparse neighborhood words due to either limited experience with the word or lack of a need to distinguish the word from neighbors.

Effects of Stimulus Characteristics on Speech Perception

The concept of lexical restructuring has implications for the perception of words with particular linguistic characteristics (e.g., age of acquisition and phonotactic probability). For the age of acquisition of words, Walley (1993) suggests that words learned early in life may be initially stored in the lexicon as more holistic representations due to the minimal competition for mental storage space. Late-acquired words, on the other hand, must be consolidated into an increasingly crowded lexicon. To distinguish these late-acquired words from representations that are already in the lexicon, the child becomes increasingly aware of the phonological structure within these words that differentiates them from

phonologically similar, previously acquired words. Processing the fine-grained phonological details within these less familiar late-acquired words is necessary for efficient word recognition, so children who are still developing this ability show poorer recognition of late-acquired words relative to early-acquired words. This age of acquisition effect has been demonstrated by improved recognition of early-acquired words as opposed to late-acquired words in children and adults with NH (Garlock, Walley, & Metsala, 2001). Age of acquisition may also interact with the child's vocabulary size during word recognition. Children with larger vocabularies, presumably, are better able to process and access late-acquired words than are children with smaller vocabularies, because children with larger vocabularies are sensitive to the fine-grained phonological structure that is necessary to distinguish late-acquired words from previously learned words. Evidence from Garlock et al. (2001) supports this perspective; in a word repetition in-noise task, they found that adults showed an advantage in repeating late-acquired words relative to older children, who showed a similar advantage relative to younger children. The differences in performance were likely due to the improved vocabularies of the older children and adults.

In addition to effects related to age of acquisition, phonotactic probability can also affect speech recognition. Particular attention has been paid to the effect of phonotactic probability on the repetition of nonwords. Phonotactic probability is the likelihood that two phonemes will co-occur in a word within a given language. Stimuli with higher phonotactic probabilities are presumably easier to recognize, but the effect of phonotactic probability on nonword repetition has been mixed. Although some studies have shown improved performance when repeating nonwords with high rather than low phonotactic probability (Edwards, Beckman, & Munson, 2004; Rispens, Baker, & Duinmeijer, 2015), others have shown no effect of phonotactic probability on nonword repetition (Janse & Newman, 2013). Further, high phonotactic probability has been shown to have a positive effect on novel word learning in both children with NH (Stiles, McGregor, & Bentler, 2013; Storkel, 2001) and children with HAs (Stiles et al., 2013). It is possible, though, that the unique auditory experiences of children with HAs may influence the probabilities of hearing-specific phoneme combinations in a way that reduces the advantage for words with high phonotactic probability that may otherwise be available to children with NH.

Similar to age of acquisition, the effect of phonotactic probability may be mediated by vocabulary size. As children acquire more words, they must develop a more segmental approach to speech perception to fit the new words into their mental lexicons. By encoding words at this fine-grained phonological level, children implicitly learn that a given phoneme can occur next to a wide range of other phonemes, instead of occurring next to only those phonemes to which it is most frequently adjacent. Children with smaller vocabularies, on the other hand, may be more restrictive in the phonetic environments in which they perceive a given phoneme to be acceptable because they do not yet give perceptual

weight to the information provided by individual phonemes. Although children with NH demonstrate this interaction between vocabulary and phonotactic probability during nonword repetition (Edwards et al., 2004), it has not been examined in children with HAs.

Vocabulary and Speech Perception in Children with HAs

Vocabulary has been identified as a factor in speech perception and word learning in children with HAs (Pittman & Schuett, 2013; Stiles et al., 2013). These studies, however, showed different patterns of speech perception and word learning between children with NH and HAs. Pittman and Schuett (2013) observed distinct error patterns in nonword detection that differed between children with NH and children with HAs, and Stiles et al. (2013) found subtly different patterns of word learning in children with HAs: Children with HAs were more likely to mistake a novel word for a semantically related foil than were children with NH. Stelmachowicz et al. (2004) also observed differential relationships between vocabulary and novel word learning in children with NH and children with HAs: Vocabulary was related to word learning in children with NH but was unrelated to word learning in similarly aged children with HAs. Taken together, these studies show mixed results regarding the relationship between vocabulary and speech recognition in children with HAs, suggesting that vocabulary growth may not drive the maturation of these children's perceptual processing in the manner proposed by lexical restructuring theories. This qualitative difference in the pattern of perceptual development may be due to the added audibility challenges faced by children with HAs, such as inconsistent audibility and delayed access to sound. In addition, although HAs increase the audibility of speech, most HAs lack the bandwidth to fully encode the high frequencies of the target signal (Kimlinger, McCreery, & Lewis, 2015), which has been shown to negatively affect access to linguistic input (Stelmachowicz, Pittman, Hoover, & Lewis, 2001, 2002) and slow word learning rates in children with HAs (Pittman, 2008). Low-level perceptual deficits may reduce access to auditory and linguistic patterns in a speech signal and thus have more of an influence on speech perception development than vocabulary. On the other hand, children with HAs tend to have smaller vocabularies than children with NH (Stiles, McGregor, & Bentler, 2012), and many studies comparing the effect of vocabulary on speech perception and word learning have not controlled for differences in vocabulary size across participants (e.g., Pittman & Schuett, 2013; Stelmachowicz et al., 2004; Stiles et al., 2013). Because of these underlying vocabulary differences, it is difficult to confidently conclude that children with HAs show developmental patterns of speech perception that are qualitatively different from those of children with NH. Instead, these differences might disappear once vocabulary size is kept comparable between the groups of children with NH and children with HAs. Walker and McGregor (2013) found a strong effect of vocabulary on word learning in children with cochlear implants, and these children did not

differ from vocabulary-matched children with NH. Although this study used children with cochlear implants instead of children with HAs, the findings support the importance of using a vocabulary-matched control group when examining the effects of vocabulary on word learning and word recognition in children with atypical auditory experience.

Other Factors to Consider: Working Memory and Audibility

When examining the effects of vocabulary and hearing status on speech perception in children with HAs, it is necessary to account for a number of other factors that are hypothesized to affect speech perception. Working memory, or the ability to store and process information, has been identified as an important factor that affects speech perception in adults with NH and adults who are hard of hearing, especially in noise (Rönnberg et al., 2013). A listener with strong working memory skills is able to hold a larger amount of speech information in the memory system at once, and this contextual information can then be used to aid in the interpretation of additional acoustically degraded speech information. Recent research has shown increased attention to the role of working memory in the speech perception of adults with hearing loss. Relatively little research in the pediatric literature has accounted for this variable when examining the speech perception of children with HAs, although McCreery et al. (2015) recently found an association between phonological working memory and speech recognition in quiet and in noise in children with HAs. McCreery, Spratford, Kirby, and Brennan (2017) also found an association between working memory and speech perception in children with NH. Working memory ability is, thus, necessary to consider when assessing the effects of other cognitive and linguistic factors, such as vocabulary.

Another relevant factor that affects the speech perception of children with HAs is audibility. Aided audibility accounts for the amount of access to speech sounds the child experiences while wearing HAs and thus is a better approximation of the child's access to sound in everyday listening situations than pure-tone average. Aided audibility is associated with word recognition in children with HAs (McCreery et al., 2015; Stiles, Bentler, et al., 2012). In a similar way, the daily amount of HA use determines the extent to which the child receives the benefits of increased audibility from the HAs. A high amount of device usage has been shown to positively influence speech perception in children with cochlear implants (Wie, Falkenberg, Tvette, & Tomblin, 2007), and it is likely to affect the speech perception of children with HAs in a similar way. Factors that directly relate to the child's auditory access must be accounted for when investigating the child's ability to extract patterns from the signal in the process of speech perception.

Current Study

The present study examines the potential facilitative effect of vocabulary on the speech perception skills of

children with HAs. The specific questions addressed by this study are the following:

1. How do age of acquisition and phonotactic probability affect word recognition and nonword repetition in children with HAs and children with NH? We predicted that late-acquired words and low-probability nonwords would result in poorer speech perception scores in both groups of children, relative to early-acquired words and high-probability nonwords.
2. How does vocabulary interact with age of acquisition and phonotactic probability to affect speech perception in children with HAs and children with NH? We predicted that children in both groups with stronger vocabulary abilities would show an advantage for late-acquired words and low-probability nonwords but not for early-acquired words or high-probability nonwords.
3. What is the effect of auditory access on the speech perception of children with HAs? We predicted that poorer access to sound (i.e., lower aided audibility and fewer hours of daily HA use) would be associated with poorer speech perception.

Method

Participants

Participants included native English-speaking children who were ages 5 to 12. Participants were recruited via a database of individuals who had previously agreed to be contacted for research studies at Boys Town National Research Hospital. Twenty-five participants (12 girls and 13 boys) were children with NH, with a mean age of 9.28 years ($SD = 2.43$) and 24 (10 girls and 14 boys) were children with HAs, with a mean age of 9.35 years ($SD = 2.06$). Children with NH all had pure-tone thresholds less than 20 dB HL at 0.5, 1, 2, and 4 kHz, bilaterally. Children with HAs had mild to severe permanent bilateral hearing loss; better ear four-frequency pure-tone average ranged from 13.8 to 77.5 dB HL ($M = 40.1$ dB, $SD = 13.9$ dB). One child with hearing loss used only one HA on a regular basis due to poor aided audibility in the opposite ear, and another child had bilateral HAs but used only one during testing due to the technical malfunction of the second HA. All other children with HAs wore bilateral HAs during the testing. The mean and range of audiograms of the children with HAs are shown in Figure 1.

Stimuli

Four word recognition conditions used stimuli that varied by age of acquisition (early vs. late) and lexical frequency (high vs. low), and two nonword repetition conditions varied by phonotactic probability (high vs. low). The late-acquired phonemes /l/, /r/, /w/, /j/, /z/, and /ŋ/ were excluded from all stimuli to minimize the effects of articulation on speech recognition, in accordance with the procedures of McCreery and Stelmachowicz (2011). All stimuli

Figure 1. Mean unaided audiometric thresholds of the children with hearing aids (HAs). Shaded area shows the range of thresholds at each frequency. Red = thresholds of right ear; blue = thresholds of left ear.

were normalized on root-mean-square amplitude and resampled at a rate of 22.05 kHz. Characteristics of the stimuli in the four word recognition conditions are provided in Table 1.

The early-acquired word recognition stimuli were within the average lexicon of 7-year-old children on the basis of the Child Mental Lexicon (CML; Storkel & Hoover, 2010), a corpus of words produced by American English-speaking kindergarten and first-grade children. A total of 512 monosyllabic early-acquired words were compiled. The lexical frequencies for each word were calculated by using the CML Calculator (Storkel & Hoover, 2010). Low and high lexical frequency words corresponded to words in the first and fourth lexical frequency quartiles of the potential words, respectively. Certain words, such as proper names and letter names, were removed from the lists. The low- and high-frequency lists were then approximately matched on initial phoneme. The low- and high-frequency early-acquired

word lists included 60 stimuli each. Lexical frequency and phonotactic probability of the early-acquired words were also calculated on the basis of the Hoosier Mental Lexicon (HML; Nusbaum, Pisoni, & Davis, 1984) to make direct comparisons of these characteristics with the late-acquired words. The HML is a database of words in the adult lexicon that includes word frequency information.

The late-acquired words appeared in the HML but did not appear in the CML. Potential monosyllabic words were drawn from adult word recognition tests (Computer-Assisted Speech Perception Assessment [Boothroyd, 1999], Northwestern University Auditory Test No. 6 [NU-6; Studebaker, Sherbecoe, & Gilmore, 1993], Central Institute for the Deaf Auditory Test W-22 [CID W-22; Studebaker & Sherbecoe, 1991], Maryland Consonant-Nucleus-Consonant-Test [CNC; Causey, Hood, Hermanson, & Bowling, 1984], and Rush Hughes Phonetically Balanced Word Lists [PB-50; Heckendorf, Wiley, & Wilson, 1997], and the English Lexicon Project online word generator [Balota et al., 2007]). Inflected forms, acronyms, words with the specified late-acquired phonemes, and words judged to be inappropriate for children (such as profanity and slang) were removed. Each of the 239 remaining words was recorded twice by the same adult speaker who recorded the early-acquired words. The best recording for each word was selected by the first author. Two adults with NH listened to and repeated each word in quiet; any word that was not correctly repeated by both listeners was removed from the list of stimuli. Word lists for low- and high-frequency late-acquired words were compiled and edited in the same way as for the low- and high-frequency early-acquired word lists so that 60 stimuli were included in each list.

The nonword stimuli varied by phonotactic probability and included a high-probability list and a low-probability list, as measured by biphone sum (Storkel & Hoover, 2010). The nonword stimuli were developed for use in McCreery and Stelmachowicz (2011). Possible nonwords were compiled by first creating a list of all possible consonant-vowel-consonant combinations that are allowed in English. Real words and slang words were removed from this list, as well as nonwords that included the specified late-acquired phonemes. Each nonword was recorded and judged intelligible by an adult with NH.

Table 1. Lexical characteristics of word recognition conditions.

Word recognition condition	Log frequency in CML	Log frequency in HML	Biphone mean in CML	Biphone mean in HML	Number of phonemes	Number of neighbors in CML	Number of neighbors in HML
Early acquired							
High frequency	3.71 (.49)	3.19 (.66)	.0038 (.0021)	.0030 (.0024)	2.93 (.36)	14.65 (6.41)	22.03 (6.39)
Low frequency	1.33 (.30)	1.85 (.62)	.0037 (.0020)	.0030 (.0023)	2.95 (.22)	13.42 (5.69)	20.37 (7.56)
Late acquired							
High frequency	—	2.24 (.46)	—	.0036 (.0028)	3.15 (.55)	—	16.47 (8.43)
Low frequency	—	1.00 (0)	—	.0036 (.0034)	3.22 (.58)	—	13.98 (7.34)

Note. Values expressed as mean (standard deviation). CML = Child Mental Lexicon; HML = Hoosier Mental Lexicon. Em dashes indicate the following: The late-acquired words are by definition not found in the CML, so the log frequency, biphone mean, and number of neighbors in the CML could not be calculated for these words.

This left 1,178 possible consonant–vowel–consonant nonwords with a biphone sum range of .0014 to .012. Low- and high-probability nonwords were drawn from nonwords in the first and fourth phonotactic probability quartiles of the potential nonwords, respectively. The final low- and high-probability lists included 60 stimuli each, matched on initial phoneme between the two lists and approximately matched to the initial phoneme distributions of the early- and late-acquired word lists. Nonwords in the high-probability condition had a mean biphone sum of .00632 ($SD = .000633$), and nonwords in the low-probability condition had a mean biphone sum of .00211 ($SD = .000328$).

A list of 10 monosyllabic words was prepared to estimate word recognition in quiet. This list included words with log frequencies of 2.3 to 2.7 in the CML and therefore were likely familiar to the participants. The 10 selected words represented diversity in initial, medial, and final phonemes and had a mean log frequency of 2.50 ($SD = 0.11$). Stimuli were presented at 65 dB SPL, and the children repeated each stimulus one at a time. This in-quiet word recognition task was completed as a screening task before the experimental conditions in noise to ensure that all participants could tolerate the basic testing procedure; poor performance on the in-quiet task would indicate a likely inability to complete it under more difficult in-noise conditions. All children performed well on this task (children with HAs, $M = 88.3\%$, $SD = 15.5$; children with NH, $M = 93.6\%$, $SD = 8.1$), and the percentage correct was not significantly different between the two groups, $F(1, 47) = 2.245$, $p = .141$.

One-way analyses of variance (ANOVAs) were used to compare biphone mean and lexical frequency between the four word recognition conditions and biphone sum between the two nonword repetition conditions. Biphone mean and lexical frequency were compared by using HML statistics instead of CML statistics because CML statistics were not available for the late-acquired words; using the HML as the reference database allowed for direct, valid comparisons of the statistics for the early- and late-acquired word recognition conditions. No significant differences were found between the biphone means of the four word recognition conditions, $F(3, 232) = 0.917$, $p = .433$, indicating that phonotactic probability did not vary systematically between the four conditions. Frequency differed significantly between the four word recognition conditions, $F(3, 232) = 192.5$, $p < .001$; Tukey post hoc analyses showed that all four conditions differed significantly on lexical frequency (see Table 1). As expected, biphone sum in the high-probability nonword condition was significantly greater than in the low-probability nonword condition, $F(1, 118) = 2093$, $p < .001$.

Language, Cognitive, and Audiologic Test Measures

Pure-tone audiometry thresholds were measured at octave frequencies (250–8000 Hz) for all children with HAs who had not had an audiogram within 6 months of the study visit. Children with NH were administered a screening audiogram at 15 dB HL if they did not have a normal audiogram on record from within the past year.

Children with NH were excluded from the study if they scored more than 1 SD below the standard score of 100 on the Goldman-Fristoe Test of Articulation–Second Edition (GFTA-2; Goldman & Fristoe, 2000). This was to ensure that the speech perception task was, in fact, measuring perception and not the child's speech production ability. The GFTA-2 was also administered to the children with HAs, but these children were still included in the study if they scored below the normal range; one child with HAs scored more than 1 SD below the standard score.

Receptive and expressive vocabulary were assessed by using the Peabody Picture Vocabulary Test–Fourth Edition (Dunn & Dunn, 2007) and the Expressive Vocabulary Test–Second Edition (EVT-2; Williams, 2007). Measures of both receptive and expressive vocabulary were administered to obtain a more complete estimate of each child's vocabulary skills than either test could provide alone. If a child had previously taken either of these tests within a month of the study visit, the test was not readministered. If a child had previously taken one of these tests 1 to 12 months before the study visit, the alternate test form (i.e., Form A or B) was administered at the study visit.

On the basis of previous research that suggests that individual differences in working memory abilities can influence speech recognition in children (McCreery et al., 2017), visuospatial and verbal working memory were assessed with the Automated Working Memory Assessment (AWMA; Alloway, 2007). Visuospatial working memory was measured with the recall score of the Odd One Out task, in which the child must recall the location of a series of items presented on the screen. Verbal working memory was measured with the Nonword Recall task, in which the child must recall progressively longer lists of nonwords presented in the sound field.

Real-ear probe microphone measures were used to measure audibility for the children with HAs. Aided Speech Intelligibility Index (SII; American National Standards Institute, 1997) at user settings were calculated through Audioscan Verifit speechmapping software (Cole, 2005). Speech was presented at 65 dB SPL following the American National Standards Institute (1997), using the standard carrot passage (Cox & McDaniel, 1989). The children with HAs group had a mean aided SII of 0.80 in the better ear ($SD = 0.15$).

At the study visit, parents of children with HAs provided separate estimates of the daily number of hours the child typically wears HAs during the school year and during the summer. These two numbers were combined to create a composite HA use score, with 75% of the composite score weight from school year HA use and 25% of the composite score weight from summer HA use. Participants had a mean daily HA use composite score of 10.2 hr ($SD = 3.55$).

Test Procedures

All word and nonword stimuli were presented by using custom MATLAB software (MathWorks, 2014) through a personal computer and an RME Babyface Universal Serial

Bus audio interface (RME Audio, Haimhausen, Germany). Stimuli were presented in the sound field through an M-Audio BX8a loudspeaker (M-Audio, Cumberland, RI) at 65 dB SPL and 0° azimuth in a sound-treated audiometric booth. The child sat 1 m in front of the loudspeaker in a chair that was adjusted so the child's head was at the approximate height of the speaker. The tester sat to the side of the speaker, facing the child. The child was instructed to repeat each item to the best of his or her ability and was encouraged to guess if unsure of the stimulus. Each child was first presented with the 10 words in quiet to become familiarized with the task, then was presented with the six in-noise test conditions. The six test conditions (high- and low-frequency early-acquired words, high- and low-frequency late-acquired words, and high- and low-probability nonwords) were presented in a random order, and the stimuli within each condition were presented in a random order. Stimuli were presented in steady-state speech-shaped wideband noise. The adaptive paradigm included two interleaved tracks and was used to estimate the signal-to-noise ratio at which the child could accurately repeat 50% of the stimuli (SNR-50). To measure the SNR-50, the noise level was increased after a correct response and decreased after an incorrect response. The minimum SNR was -20 dB, and the maximum SNR was 60 dB. The noise level was changed by a step size of 18 dB after presenting the first stimulus, 9 dB after the second stimulus, 6 dB after the third stimulus, and 3 dB for all subsequent stimuli. The tester scored each item as either correct or incorrect, and a given item was presented a second time only when the child was speaking or making other sounds (e.g., coughing or laughing) during the first presentation of the stimulus. Once both tracks had reached six reversals within a condition, the condition concluded. Thus, each child was presented with fewer than the 60 possible stimuli within a given condition. The SNR-50 for each track was the mean of the SNRs corresponding to the last three reversal points for that track. The final SNR-50 for each condition was the mean of the SNRs provided by the two tracks.

For an item to be scored as correct, all phonemes needed to be present: Insertions and omissions of sounds caused the item to be scored as incorrect. Mispronunciations were accepted as correct only if it was determined during previous testing and conversation with the child that the child consistently mispronounced the specified sound in the same way. Furthermore, the mispronunciation was only accepted as a correct substitution during the speech perception task if the mispronounced sound produced by the child was distinguishable from all other phonemes in English. If the child consistently substituted one English phoneme with another, the substitution was scored as incorrect.

Statistical Analyses

Statistical analyses were performed using R Version 3.2.1 (R Core Team, 2015) and the packages ggplot2 (Wickham, 2009), lsr (Navarro, 2015), lmerTest (Kuznetsova, Brockhoff, & Christensen, 2015), and lme4 (Bates, Maechler, Bolker, & Walker, 2015). One-way ANOVAs were used

to compare the children with NH and children with HAs on age, receptive vocabulary, expressive vocabulary, articulation, and verbal and visuospatial working memory. One-way ANOVAs were used to compare the word recognition and nonword repetition conditions on lexical frequency and phonotactic probability to ensure that the six conditions varied by the expected characteristics, without confounding variables.

Individual data points were excluded from analysis when it was suspected that the child was not appropriately attending to the speech perception task during a particular condition. In particular, a data point was removed when the mean of the two condition tracks for the child was greater than 20 dB SNR and the difference between the two tracks was greater than 10 dB. It was determined that SNRs greater than 20 dB include a signal that is presented essentially in quiet. Furthermore, inconsistent SNRs between tracks within a single condition for a given child indicate that the child likely was not investing consistent effort or attention into the task during that condition. Removing data points on the basis of the previously mentioned criteria resulted in the exclusion of 14 participant conditions, 13 of which were from children with HAs. One more child's condition was excluded because both tracks for the condition had SNRs of 59 dB, which was essentially at the maximum SNR of 60 dB. No child had more than three of their six conditions excluded from analysis. The following number of data points were removed from each of the six conditions (all from children with HAs, unless otherwise specified): one from early-acquired high-frequency words; two from early-acquired low-frequency words; two from late-acquired high-frequency words; two from late-acquired low-frequency words; three from high-probability nonwords (one child who is NH); and six from low-probability nonwords.

To evaluate predictors of speech perception performance, linear mixed models were used. Unlike linear regression, linear mixed models allow the specification of correlation of outcome measures obtained from the same participants and a variance component to the model that allows the intercept of the model to vary randomly across individual participants. The linear mixed models included a random intercept term that allowed the intercept to vary across participants to account for differences in speech recognition abilities across children. The first mixed model examined predictors of performance in the four word recognition conditions (predictors: age, hearing status, expressive vocabulary, and age of acquisition), and the second model was used to predict performance in the two nonword repetition conditions (predictors: age, hearing status, expressive vocabulary, and phonotactic probability). A third mixed model examined predictors of performance across all six speech perception conditions for the children with HAs only (predictors: aided audibility, amount of daily HA use, verbal working memory, and expressive vocabulary). All predictor variables were mean-centered to minimize the possibility of multicollinearity. Model assumptions were assessed through residual evaluation, and no evidence of assumption violation was found.

Results

Comparison of Language and Cognitive Measures in Children With HAs and Children With NH

One-way between-participants ANOVAs were conducted to compare children from both groups on age, receptive vocabulary (Peabody Picture Vocabulary Test–Fourth Edition), expressive vocabulary (EVT-2), articulation (GFTA-2), and verbal and visuospatial working memory (AWMA Nonword Recall and Odd One Out, respectively; see Table 2). Separate one-way ANOVAs were used to compare raw and standard scores between the two groups. Children with NH had significantly higher Nonword Recall raw scores than children with HAs, $F(1, 46) = 12.00, p = .001$, as well as significantly higher Nonword Recall standard scores, $F(1, 46) = 13.31, p < .001$. No significant differences were found between the two groups on any of the language measures or on visuospatial working memory. Correlations between select cognitive and linguistic measures and SNR-50 in the six speech perception conditions are presented in Table 3.

Effects of Age of Acquisition and Vocabulary on Word Recognition

Three mixed models were used to examine predictors of SNR-50 in the word recognition and nonword repetition conditions. Model selection was based on the stated

Table 2. Linguistic and cognitive characteristics of children with HAs and children with NH.

Parameter	Hearing status	<i>M</i> (<i>SD</i>)	<i>F</i> value	<i>p</i> value
Age (years)	NH	9.3 (2.4)	0.01	.91
	HAs	9.4 (2.1)		
PPVT-4 (raw score)	NH	155.0 (31.8)	0.47	.50
	HAs	148.5 (35.1)		
PPVT-4 (standard score)	NH	113.0 (13.6)	2.50	.12
	HAs	106.3 (15.7)		
EVT-2 (raw score)	NH	115.6 (30.5)	0.02	.89
	HAs	114.3 (29.5)		
EVT-2 (standard score)	NH	108.9 (13.8)	0.29	.59
	HAs	106.4 (18.0)		
GFTA-2 (raw score)	NH	1.5 (4.3)	0.17	.69
	HAs	2.0 (3.9)		
GFTA-2 (standard score)	NH	103.7 (3.7)	2.43	.13
	HAs	101.3 (6.8)		
AWMA Nonword Recall (raw score)	NH	12.7 (3.3)	12.00	.001
	HAs	8.8 (4.6)		
AWMA Nonword Recall (standard score)	NH	103.3 (11.7)	13.31	<.001
	HAs	88.4 (16.5)		
AWMA Odd One Out Recall (raw score)	NH	19.7 (7.2)	0.13	.72
	HAs	20.3 (5.3)		
AWMA Odd One Out Recall (standard score)	NH	110.4 (13.5)	0.33	.57
	HAs	112.7 (14.1)		

Note. HAs = hearing aids; NH = normal hearing; PPVT = Peabody Picture Vocabulary Test–Fourth Edition; EVT = Expressive Vocabulary Test–Second Edition; GFTA = Goldman-Fristoe Test of Articulation–Second Edition; AWMA = Automated Working Memory Assessment.

hypotheses. Each model included a random intercept for each participant.

The first mixed model was used to examine predictors of SNR-50 across the four word recognition conditions. In particular, this mixed model tested our predictions that children with larger vocabularies would show an advantage for recognizing late-acquired words, but not early-acquired words (Question 2), and that word recognition would be better for early-acquired words than late-acquired words in both children with NH and children with HAs (Question 1). This model included main effects of age, hearing status, EVT-2 raw score, age of acquisition, and lexical frequency, as well as the interactions between EVT-2 raw score, age of acquisition, and lexical frequency. There were significant main effects of hearing status, $t(42.84, 178) = 5.78, p < .001$, and age of acquisition, $t(135.36, 178) = 3.05, p = .0028$, on SNR-50, while no significant main effect of age or EVT-2 raw score was found ($p > .05$). Also, the EVT-2 raw score and age of acquisition showed a significant interaction effect, $t(136.23, 188) = -2.27, p = .025$, indicating that children with larger vocabularies showed better word recognition than children with smaller vocabularies for the late-acquired words but not for the early-acquired words (see Figure 2). This pattern was the same for both groups of children. None of the other higher order interactions were significant. The main effects of hearing status and age of acquisition indicate that children with HAs and late-acquired word conditions resulted in a higher SNR-50 than children with NH and early-acquired words, respectively. This supports our prediction that performance would be better in the early-acquired word recognition conditions. Table 4 displays a comparison of the performance in each of the six conditions for the two groups.

Effects of Phonotactic Probability and Vocabulary on Nonword Repetition

A second mixed model was used to test the following predictions: Children would show better repetition of high-probability than low-probability nonwords (Question 1), and children with larger vocabularies would show an advantage in nonwords with low phonotactic probability but not with high phonotactic probability (Question 2). This model included the factors of age, hearing status, EVT-2 raw score, and phonotactic probability, which were used to predict SNR-50 across the two nonword repetition conditions. The interaction between expressive vocabulary and phonotactic probability was also tested. Hearing status, $t(39.43, 81) = 6.38, p < .001$, and EVT-2 raw score, $t(51.27, 81) = -2.42, p = .019$, showed significant main effects on SNR-50 (see Figure 3). Hard of hearing status and low EVT-2 raw score were associated with higher SNR-50 in the nonword conditions. No significant main effect of age or phonotactic probability was found, and no significant interaction effect between EVT-2 raw score and phonotactic probability was found ($p > .05$). These findings do not support our prediction that vocabulary would selectively enhance performance for low-probability nonword repetition. In addition, our

Table 3. Correlations between age, cognitive and linguistic factors, amplification factors, and speech perception scores in children with HAs.

Parameter	Age	EVT raw score	Verbal WM	Visuospatial WM	Aided audibility	Better ear PTA	HA use	Early acquired, high frequency	Early acquired, low frequency	Late acquired, high frequency	Late acquired, low frequency	Nonword, high probability	Nonword, low probability
Age	1	.75***	.31	.54**	.35	-.37	-.35	-.19	-.25	-.36	-.51*	-.40	.29
EVT-2 raw score	1		.52*	.65***	.33	-.40	-.16	-.22	-.20	-.54*	-.65**	-.59**	-.16
Verbal WM			1	.11	.55**	-.66***	-.41	-.33	-.46*	-.35	-.46*	-.38	-.30
Visuospatial WM				1	.25	-.28	-.24	-.23	-.12	-.39	-.47*	-.51*	.08
Aided audibility					1	-.86***	-.60**	-.43*	-.61**	.00	-.55**	-.23	.25
Better ear PTA						1	.52**	.23	.45*	.19	.44*	.32	-.21
HA use							1	.26	.27	-.25	.18	-.04	-.29
Early acquired, high frequency								1	.58**	.33	.45*	.50*	.38
Early acquired, low frequency									1	.49*	.72***	.16	.10
Late acquired, high frequency										1	.70***	.64**	.39
Late acquired, low frequency											1	.61**	.28
Nonword, high probability												1	.60*
Nonword, low probability													1

Note. HAs = hearing aids; EVT = Expressive Vocabulary Test–Second Edition; WM = working memory; PTA = pure-tone average.

* $p < .05$. ** $p < .01$. *** $p < .001$.

Figure 2. The signal-to-noise ratio at which the child could accurately repeat 50% of the stimuli (SNR-50) across the four word recognition conditions. EVT-2 = Expressive Vocabulary Test–Second Edition; HAs = children with hearing aids; NH = children with normal hearing.

prediction that recognition would be higher for nonwords with higher phonotactic probability was not confirmed, because neither group showed an effect of phonotactic probability. Overall children with HAs showed poorer nonword repetition ($M = 11.84$ dB, $SD = 5.65$) than children with NH ($M = 4.57$ dB, $SD = 4.21$).

Effects of Cognitive-Linguistic Factors and Auditory Access on Speech Perception in Children With HAs

A third mixed model was used to examine the effects of aided audibility and daily HA use on speech perception in children with HAs (Question 3). This model included the factors of better ear aided SII, HA use composite score, Nonword Recall raw score, and EVT-2 raw score. These factors were used to predict SNR-50 across all six word and nonword conditions for children with HAs. Data from all six conditions were pooled as the dependent variable in a single mixed model. A significant main effect of EVT-2 raw score on speech perception was found in this group, $t(19.24, 118) = -2.51$, $p = .021$. This indicates that after controlling for auditory access and working memory, a large expressive vocabulary continues to be uniquely associated

with speech perception abilities in children with HAs. None of the other factors showed a significant main effect on SNR-50 ($p > .05$), which contradicts the prediction that children with HAs with more consistent auditory access would have better speech perception.

Discussion

The goals of this study were to assess (a) the effects of age of acquisition and phonotactic probability on word recognition and nonword repetition, respectively, in children with HAs and children with NH, (b) the effect of vocabulary on word recognition and nonword repetition in children with HAs and children with NH, specifically the interaction effects between vocabulary and age of acquisition and phonotactic probability, and (c) the effect of auditory access on the word recognition and nonword repetition of children with HAs. We predicted that all children would have better recognition of early-acquired words and better repetition of high phonotactic probability nonwords. We, furthermore, predicted that children in both groups with stronger vocabulary abilities would show an advantage for late-acquired words and low phonotactic probability nonwords but not for

Table 4. Group SNR-50 scores for each listening condition.

Parameter	Early acquired, high frequency	Early acquired, low frequency	Late acquired, high frequency	Late acquired, low frequency	High phonotactic probability	Low phonotactic probability
Children with NH	1.00 (3.77)	1.72 (4.00)	0.42 (4.72)	2.72 (3.79)	4.73 (4.06)	4.42 (4.62)
Children with HAs	5.42 (5.60)	5.89 (3.29)	5.95 (7.07)	9.70 (8.49)	12.98 (7.12)	10.44 (2.62)
p	.002	<.001	.002	<.001	<.0001	<.0001
Cohen's d	0.95	1.17	0.95	1.10	1.46	1.54

Note. Scores shown as mean (standard deviation). SNR-50 = the signal-to-noise ratio at which the child could accurately repeat 50% of the stimuli; NH = normal hearing; HAs = hearing aids.

Figure 3. The signal-to-noise ratio at which the child could accurately repeat 50% of the stimuli (SNR-50) across the two nonword repetition conditions. EVT-2 = Expressive Vocabulary Test–Second Edition; HAs = children with hearing aids; NH = children with normal hearing.

early-acquired words and high phonotactic probability nonwords. Also, we predicted that poor aided audibility and low HA use would negatively affect speech perception performance in children with HAs.

Early age of acquisition was associated with better performance in the word recognition conditions for both children with HAs and children with NH, confirming our prediction related to Question 1. Furthermore, age of acquisition interacted with expressive vocabulary in predicting word recognition SNR-50. Relative to children with smaller vocabularies, children with larger vocabularies showed a greater benefit for late-acquired words than early-acquired words. This interaction supported our prediction regarding the advantage of higher vocabulary for later acquired words (Question 2). Contrary to the original predictions, phonotactic probability did not affect nonword repetition, and differences in expressive vocabulary did not predict which children would be better able to use phonotactic cues during nonword recognition (Questions 1 and 2). Although children with HAs demonstrated poorer word recognition and nonword repetition than children with NH across all conditions, the auditory access factors examined (i.e., daily HA use composite score and better ear aided SII) were not significantly associated with speech perception, which differed from our prediction to Question 3. No significant interactions were shown between hearing status and age of acquisition, phonotactic probability, or lexical frequency, indicating that children with HAs and children with NH were similarly affected by these factors.

Evidence of Deficits in Phonological Sensitivity in Children With HAs

Although children in the two groups performed comparably on most measures of cognitive and linguistic skills, children with HAs performed significantly worse on the Nonword Recall subtest of the AWMA, which measures

verbal working memory and requires the child to repeat progressively longer lists of nonwords presented in quiet. To accurately repeat all the phonemes within the nonwords, the child must have sensitivity to the phonological structure within the stimuli. Because children with HAs performed similarly to children with NH on the measure of visuospatial working memory (nearly 1 *SD* above the normative mean), it is unlikely that the poor performance on the Nonword Recall task in children with HAs is due to deficits in general working memory skills. Rather, the results of the Nonword Recall task indicate that the children with HAs showed a deficit in sensitivity to the internal phonological structure of the stimuli, which is necessary for the accurate processing and repetition of nonwords. Also, on the speech perception in noise task, children with HAs performed the poorest in the conditions that used stimuli consisting of nonwords rather than real words. Similar to the Nonword Recall task, these conditions require that the child attend to the specific phonological structure within the nonwords; in contrast to the known real words, the child cannot rely on previous experience with the nonwords to repeat them correctly. The poor performance of the children with HAs in the nonword repetition conditions suggests a likely deficit in sensitivity to phonological structure in these children. The poorer performance of the children with HAs in the late-acquired word recognition conditions relative to the early-acquired word recognition conditions further supports this perspective, as unfamiliar words are expected to be processed in the same way as nonwords. Although the results collectively support the idea that children with HAs show a decreased ability to make use of the fine-grained phonological structure within words, it is unlikely that these children are completely insensitive to this information. Despite the relatively poor performance of the children with HAs in the nonword repetition conditions, the majority of children were able to accurately repeat the nonwords in the presence of considerable background noise, indicating some degree

of sensitivity to phonological structure. The finding of decreased phonological sensitivity is informative in light of the strong vocabulary skills shown by the children with HAs in this study because it demonstrates that these children are capable of building robust lexicons, despite showing weak access and sensitivity to phonological structure.

Evidence of Lexical Restructuring in Children With HAs

The present study shows that the speech perception of children with HAs was not differentially affected by vocabulary compared with children with NH. In particular, the results support the idea that children with HAs undergo lexical restructuring due to vocabulary development in a manner that is similar to children with NH. Although the speech perception task used in the present study was not designed specifically to assess children's sensitivity to fine-grained phonological structure, the pattern of results do not provide any evidence for the idea that children with HAs differ in their speech-processing mechanisms relative to children with NH. Many researchers (Charles-Luce & Luce, 1995; Metsala, 1997; Nitttrouer & Lowenstein, 2007; Storkel, 2002; Ventura et al., 2007; Walley, 1993) have hypothesized that vocabulary growth leads to increased density of exemplars in the mental lexicon, which necessitates that the listener perceptually attend to the fine-grained phonological structure within words, rather than processing each word holistically. The extension of this theory to include children with HAs along with children with NH is supported by the observed interaction effect between vocabulary and age of acquisition on word recognition in children with HAs, as well as the main effect of vocabulary on nonword repetition in children with HAs. Because these relationships persist even after controlling for age, it is likely that these differences in speech perception truly are driven by vocabulary development, rather than by the more general maturational effects of age. Although the two groups show evidence of lexical restructuring, the poorer sensitivity of children with HAs to phonological structure indicates that they had likely not experienced as much lexical restructuring as children with NH. It is, however, unlikely that these children relied on purely holistic word representations, considering their ability to complete the nonword repetition tasks. It is unclear if children with HAs experience a delayed process of lexical restructuring that will eventually become equivalent to that of children with NH or if children with HAs experience a limit in the extent to which lexical restructuring is possible. The process of lexical restructuring is gradual, and a better understanding of the time course of this process in children with HAs will improve our understanding of the processes underlying these children's speech perception. This should be examined in future research.

A limitation of the current study is that, with children between the ages of 5 and 12 years, the age range of participants was large. A substantial amount of cognitive and linguistic development occurs within this age range. Thus, it is difficult to conclude definitively that the observed

effects on speech perception were due to vocabulary growth specifically, rather than improvements in different language areas. Future research should work to identify factors associated with speech perception in children with HAs during narrower windows of development to better understand the specific contributions of vocabulary to speech perception in these children throughout childhood.

Effect of Hearing Status on Speech Perception

There was a main effect of hearing status (i.e., NH vs. hard of hearing) on both word recognition and nonword repetition, with children with HAs showing poorer overall performance on both tasks than children with NH. The poorer performance of children with HAs conforms to the findings of past studies (Finitzo-Hieber & Tillman, 1978; McCreery et al., 2015; Stiles, Bentler, et al., 2012) and may be due to the limited spectral resolution or low-pass filtering of HAs. These features reduce access to speech sounds and may impair the overall ability to make use of the phonological structure within words. Children with HAs, interestingly, showed receptive and expressive vocabulary scores that were, overall, slightly higher than the standardized mean scores, in contrast to past studies that have found that children with HAs tend to have smaller vocabularies than children with NH (Davis, Stelmachowicz, Shepard, & Gorga, 1981; Mayne, Yoshinaga-Itano, & Sedey, 1999; Pittman, Lewis, Hoover, & Stelmachowicz, 2005; Pittman & Schuett, 2013; Stelmachowicz et al., 2004; Stiles, McGregor, et al., 2012). It appears that reduced sensitivity to fine phonological structure does not necessarily prevent children with HAs from developing robust vocabularies (Tomblin et al., 2015). Furthermore, overall performance differences in speech perception between children with NH and children with HAs persist even though the groups had similar abilities in most areas of language and working memory. Further research is needed to investigate the specific causes of speech perception deficits in children with HAs; Caldwell and Nitttrouer (2013) have hypothesized that these deficits may be related to limited access to phonological structure due to the impoverished signal provided by the HAs and impairments in phonological awareness. Although these deficits in speech perception are important to consider, the goal of this study was to examine the underlying processes of speech perception, rather than overall speech perception ability. For this reason, the remainder of this discussion will focus on the observed effects on speech perception of varying vocabulary, age of acquisition, phonotactic probability, and auditory access. These effects are interpreted as representing the mechanisms underlying speech perception and—in contrast to the more static measure of overall speech perception—appear to be parallel in both children with HAs and children with NH.

Effect of Phonotactic Probability on Speech Perception

The lack of an effect of phonotactic probability on nonword repetition in either group was surprising and is in

contrast with previous studies that show high-probability sequences are easier to repeat than low-probability sequences (Edwards et al., 2004; Vitevitch & Luce, 1998, 2005; but see Janse & Newman, 2013). Perhaps the discrepant results found in this study were due to the unique demands of the specific task that was used. Listening in noise obscures some of the acoustic-phonetic information available to the child. When a real word is familiar, the available acoustic cues increase the a priori probability of the stimulus being a word that contains those cues. In contrast, when the target is a nonword, the child cannot rely on past experiences with lexical probabilities to determine the nonword. Perhaps the effect of phonotactic probability is only evident when all the acoustic-phonetic information of a stimulus is accessible to the child. Janse and Newman (2013) found no significant effect of phonotactic probability when young adults were asked to repeat nonwords presented in noise, which supports the idea that adding noise to a nonword repetition task may obscure the possible perceptual benefit of high phonotactic probability. The finding that neither the children with HAS nor the children with NH showed an effect of phonotactic probability, though, further supports the notion that children with HAS were not differentially affected by stimulus characteristics compared with children with NH. In other words, children with HAS were not missing out on linguistic cues (such as phonotactic probability) that helped facilitate speech perception in children with NH.

Effect of Auditory Access on Speech Perception in Children With HAS

The lack of an effect of aided audibility and daily HA use on speech perception in children with HAS was also surprising, because past studies have found effects of both aided audibility (McCreery et al., 2015; Scollie, 2008; Stelmachowicz et al., 2000) and device use (McCreery et al., 2015; Wie et al., 2007). This null finding is likely due to the characteristics of the particular sample of children with HAS who enrolled in the present study. In general, this group of children had appropriate aided audibility for their degree of hearing loss and consistent device usage. The lack of substantial variation among children on these auditory access factors makes it unlikely that an effect of these factors could have been observed (McCreery et al., 2015). Further research should include children with HAS who experience a broader range of auditory access with their HAS.

Theoretical Implications

The evidence for lexical restructuring in children with HAS is important because it provides insight into the underlying mechanisms of speech perception of children with HAS. In particular, these findings suggest that vocabulary growth drives the development of mature speech perception, which includes increased attention to the phonological structure within words (Nitttrouer, 1996; Nitttrouer & Lowenstein, 2007). Speech perception, in turn, lays the groundwork for

word learning (Werker & Yeung, 2005): A novel word may not develop a robust representation in the mental lexicon if the child cannot accurately perceive the spoken form of the word. Word learning then contributes to further vocabulary growth. In this way, vocabulary size and word learning ability contribute to the development of one another through a self-perpetuating cycle, which appears to be mediated by the fine perceptual processing of speech. The finding that a larger vocabulary was related to better perception of the most unfamiliar stimuli used in this study (i.e., late-acquired words and nonwords) for children with HAS indicates that these children with the largest vocabularies are best equipped to perceive novel words and assimilate these word forms into their lexicons. This effect may be especially prominent when listening conditions cause the speech signal to be degraded, such as in a noisy environment. The finding that expressive vocabulary size of children with HAS continued to be a significant predictor of speech perception after auditory access was accounted for further indicates that vocabulary has a unique effect on speech perception. This relationship between vocabulary and speech perception also helps to shed light on the findings of past studies (Pittman et al., 2005; Stiles et al., 2013) that showed poorer word learning in children with HAS than children with NH. In these studies, children with HAS had overall smaller vocabularies than their NH peers. Because vocabulary size appears to be a driving force in word learning for children with HAS, an early focus on vocabulary growth in children with HAS may help prepare them for the more demanding task of assimilating novel words into a crowded mental lexicon later on. It must be acknowledged, though, that due to the cross-sectional nature of the present study, the direction of the association between fine-grained phonological processing of speech and vocabulary size cannot be determined definitively. The causal relationship may be in the opposite direction so that sensitivity to phonological structure leads to more efficient vocabulary growth. Longitudinal studies are needed to determine the direction of the association between these factors. However, the current interpretation that vocabulary growth leads to increased awareness of word-internal phonological structure is supported by the large body of research that has proposed the phenomenon of lexical restructuring (e.g., Charles-Luce & Luce, 1995; Metsala, 1997; Storkel, 2002; Ventura et al., 2007; Walley et al., 2003).

Clinical Implications

The findings of this study have implications for clinical speech perception tasks used with children with HAS. Assessments, such as the Lexical Neighborhood Test (Kirk, Pisoni, & Osberger, 1995), are used to indirectly assess the interaction between peripheral hearing loss and underlying central processes of word recognition by varying the lexical characteristics of the test items. At present, there are no widely used clinical tests of speech perception that explicitly compare recognition of early- and late-acquired words. In fact, a prevailing strategy to minimize the influence of language ability on clinical speech recognition is to select

stimuli that are within the average lexicon of children who are being tested. To understand how children who are deaf and hard of hearing perceive speech in real-world listening environments, it is necessary to account for the resources these children have available to them while listening to speech, including vocabulary and other cognitive factors. A clinical speech perception task that varies word age of acquisition may help clinicians better understand the extent to which vocabulary and other cognitive factors influence speech perception across a range of lexical content in children who are deaf and hard of hearing. McCreery et al. (2015) found that children with HAs showed less performance variability on the Lexical Neighborhood Test than on a speech in noise task that used adult words, indicating that the use of late-acquired words may increase the sensitivity of speech perception measures for children with HAs.

Conclusion

In this study, expressive vocabulary was found to facilitate the perception of late-acquired words and non-words more than the perception of early-acquired words in both children with HAs and children with NH. Auditory access (i.e., aided audibility and HA use) did not have a direct effect on speech perception of the children with HAs; however, the sample of children with HAs used in this study showed only limited variation on these measures. These findings support the idea that when their auditory access is relatively good, children with HAs are able to take advantage of strong vocabulary skills in the same way as their peers with NH. This pattern of results may reflect parallel underlying mechanisms of speech perception in children with HAs and children with NH, but further research that more explicitly measures speech processing in children with HAs and children with NH is needed to verify this theory. Despite being closely matched on age, language, and working memory abilities, children with HAs showed overall poorer speech perception than children with NH. Although supporting vocabulary development in children with HAs may aid in their ability to perceive and acquire new words, further investigation is needed to understand the causes of the gap that exists between the overall speech perception abilities of children with HAs and children with NH.

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