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Delayed lexical access and cascading effects on spreading semantic activation during spoken word recognition in children with hearing aids and cochlear implants: Evidence from eye-tracking

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Abstract

Objective: The objective of this study was to characterize the dynamics of real-time lexical access, including lexical competition among phonologically similar words, and spreading semantic activation in school-age children with hearing aids (HAs) and children with cochlear implants (CIs). We hypothesized that developing spoken language via degraded auditory input would lead children with HAs or CIs to adapt their approach to spoken word recognition, especially by slowing down lexical access.

Design: Participants were children ages 9-12 years old with normal hearing (NH), HAs, or CIs. Participants completed a Visual World Paradigm task in which they heard a spoken word and selected the matching picture from four options. Competitor items were either phonologically similar, semantically similar, or unrelated to the target word. As the target word unfolded, children's fixations to the target word, cohort competitor, rhyme competitor, semantically related item, and unrelated item were recorded as indices of ongoing lexical access and spreading semantic activation.

Results: Children with HAs and children with CIs showed slower fixations to the target, reduced fixations to the cohort competitor, and increased fixations to the rhyme competitor, relative to children with NH. This wait-and-see profile was more pronounced in the children with CIs than the children with HAs. Children with HAs and children with CIs also showed delayed fixations to the semantically related item, though this delay was attributable to their delay in activating words in general, not to a distinct semantic source.

Conclusions: Children with HAs and children with CIs showed qualitatively similar patterns of real-time spoken word recognition. Findings suggest that developing spoken language via degraded auditory input causes long-term cognitive adaptations to how listeners recognize spoken

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words, regardless of the type of hearing device used. Delayed lexical access directly led to delays in spreading semantic activation in children with HAs and CIs. This delay in semantic processing may impact these children's ability to understand connected speech in everyday life.

INTRODUCTION

Childhood hearing loss (HL) is a common condition, affecting approximately 3% of children and adolescents in the United States (Mehra et al., 2009). Hearing aids (HAs) and cochlear implants (CIs) can improve access to speech, but these devices are imperfect: HAs are poor at transmitting high frequencies (Stelmachowicz et al., 2000) and CIs do not clearly separate frequencies. Due to their degraded and often inconsistent access to speech signals, children with any degree of HL are at risk for problems developing spoken language and listening skills (e.g., Tomblin et al., 2015), especially in higher-level language. Many school-age children with HL perform within the normative range on standardized measures of vocabulary and grammar (Halliday et al., 2017; Klein et al., 2017; Lund, 2016; Nittrouer et al., 2020; Nittrouer et al., 2018; Wie et al., 2020), yet they lag behind their normal-hearing (NH) peers on more complex tasks like understanding sequential directions, ambiguous sentences, or multi-sentence stories (Griffin et al., 2020; Lewis et al., 2015; Nittrouer & Lowenstein, 2021; Walker et al., 2020), and recognizing malapropisms (Lowenstein & Nittrouer, 2021). These complex aspects of spoken language are likely to be crucial for classroom success (Lowenstein & Nittrouer, 2021).

To develop effective interventions, it is necessary to pinpoint the underlying cause of higher-level spoken language deficits in children with HL. One possible explanation is that lower-level language skills of these children are intact, but their degraded input or inconsistent access limits their ability to develop more complex spoken language and listening skills. An alternative explanation is that children with HL experience subtle deficits in lower-level language skills, but these deficits are missed by most standardized assessments. It is possible that small differences in lower-level skills (such as a delay in recognizing individual words) compound into greater difficulties in the context of more complex multi-sentence speech input.

One such lower-level skill is real-time spoken word recognition. In the guise of accuracy, word recognition is a useful outcome measure for listeners with HL. However, even in listeners with NH, word recognition is a complex, cognitively rich process that unfolds over time (Dahan & Magnuson, 2006). The process of word recognition unfolds over several hundred milliseconds and affords multiple dimensions in which individuals can vary over development or across levels of hearing or language ability (cf. McMurray et al., in press). Thus, examining the real-time processes by which children with HL recognize words may reveal a deficit that is not detected by standard accuracy measures, and it may reveal how the specific aspects of these processes differ. If children with HL show similar dynamics of real-time spoken word recognition as children with NH, it would suggest that the lower-level lexical skills of children with HL are intact, and children with HL simply struggle to apply those skills in more demanding language situations. On the other hand, if children with HL differ from children with NH in how they approach real-time word recognition, these lower-level differences may scale up to lead to more pronounced higher-level spoken language deficits (Kronenberger & Pisoni, 2019).

The present study used eye-tracking in the Visual World Paradigm (VWP) to characterize the cognitive mechanisms that children with HL use to resolve competition among phonological competitors and recognize words. To start to ask how lower-level skills could cascade to affect higher level spoken language, we also ask how differences in these basic word recognition mechanisms are related to differences in how children with HL process word-level semantics.

Lexical Access during Spoken Word Recognition

Even under ideal listening conditions, word recognition is complex. Speech unfolds over time, raising the problem of temporary ambiguity: at any given moment, a listener likely has not yet heard the complete word. For example, when a listener hears the word *sandal*, upon hearing *san-* they cannot know if the target word is *sandal* or *sandwich*.

Adults with NH address the problem of temporary ambiguity by using immediate competition and incremental processing. As soon as any auditory input arrives, listeners make inferences about likely words, immediately activating multiple lexical candidates (e.g., *sandal* and *sandwich*) that are consistent with the signal (*san*-) up to that point (Allopenna et al., 1998; Luce & Pisoni, 1998; Marslen-Wilson, 1987; McClelland & Elman, 1986; Zwitserlood, 1989). The relative activation of these lexical candidates is updated as more auditory input arrives. Lexical competition is thus a direct result of incremental processing. As more input arrives to disambiguate the target from other candidates, the listener resolves the lexical competition by suppressing incorrect competitors (*sandwich*) as the listener becomes more confident in the identity of the target word (*sandal*).

Lexical competition can be seen as a largely passive process that reflects whatever words are consistent with the auditory input thus far. However, it is far more complex. Listeners activate rhymes (e.g., *sandal* and *candle*) even though they can be ruled out from the first phoneme (Allopenna et al., 1998; Connine et al., 1993). Further, factors such as word frequency (Dahan, Magnuson, & Tanenhaus, 2001), neighborhood density (Apfelbaum et al., 2011; Luce & Pisoni, 1998; Magnuson et al., 2007), and lexical inhibition (Dahan, Magnuson, Tanenhaus, et al., 2001) also affect the timing and extent to which listeners activate lexical candidates. Finally, the dynamics of spoken word recognition develop slowly, through adolescence (Rigler et al., 2015). Together, these findings indicate that spoken word recognition is a complex and flexible process that is tuned over development to balance efficiency and accuracy (McMurray et al., in press).

An effective tool for precisely characterizing the time course of lexical competition is the Visual World Paradigm (VWP; Tanenhaus et al., 1995). In the VWP, participants hear a word and match it to a picture of its referent on a screen containing multiple pictures. Pictures instantiate candidates that may compete. For example, for the target word *sandal,* pictures may include a *sandwich* (a cohort competitor, i.e., a word beginning with the same phonemes as the target) and a *candle* (a rhyme, i.e., a word ending with the same phonemes as the target) along with the target and an unrelated item. As participants perform this task, they make one or more eye movements to prepare the response. Participants can make 3-5 fixations per second while word recognition is unfolding. The amount that the participant is looking at a particular picture at a given moment is based in part on the degree to which the participant is activating the lexical representation of the picture's label at that moment. In VWP analyses, fixations are aggregated across trials to provide the proportion of fixations to each item type at each timepoint after target word onset. These fixation probabilities reflect the underlying lexical activation of each word, accounting for intervening processes such as visual search and oculomotor control (e.g., Allopenna et al., 1998; Magnuson, 2019).

Effects of Degraded Input on Spoken Word Recognition

Researchers have recently used the VWP to begin to ask how signal degradation affects lexical access and competition. This has identified two profiles of lexical competition that appear across studies. One profile can be termed *sustained competitor activation* (Farris-Trimble et al., 2014). This profile is characterized by increased competitor activation that is sustained over time, often in combination with small delays in target word activation. Listeners initiate lexical access immediately upon hearing the start of the word, but then are slow to suppress activation of competitors because it is possible that one of those competitors may be the target. This approach may allow for easier later revisions if the initial perception was not correct (Winn & Teece, 2021). The sustained competitor activation profile has been demonstrated in adults with NH listening to speech in background noise (Ben-David et al., 2011; Brouwer & Bradlow, 2016), 8-channel noise-vocoded speech (Farris-Trimble et al., 2014), and slightly soft speech (Hendrickson et al., 2020). It has also been shown in postlingually deaf adults with CIs listening to speech in quiet (Farris-Trimble et al., 2014; Nagels et al., 2020). All these situations include only a moderate amount of uncertainty about the speech signal.

The alternative profile has been colloquially termed *wait-and-see* (McMurray et al., 2017). In this profile listeners do not process speech as incrementally, and instead wait until substantial auditory input accrues before activating any candidates. Because of this delay, listeners appear to activate cohorts *less* than they would with a clear signal because by the time lexical competition is underway, more information is available to rule the cohorts out. In contrast, listeners activate rhyme competitors more than they would with a clear signal. The wait-and-see profile has been demonstrated by NH adults and children listening to very soft speech (Hendrickson, Oleson, et al., 2021; Hendrickson et al., 2020), NH adults listening to highly degraded 4-channel vocoded speech (McMurray et al., 2017), and prelingually deaf adolescents with CIs (McMurray et al., 2017). All these situations involve highly degraded listening conditions and high uncertainty about the speech signal. The wait-and-see profile may be an adaptive approach to reducing perceptual errors, though it comes at the cost of recognizing words slower. Importantly, wait-and-see represents a substantial departure from the immediate competition approach that was long thought to be the universal way of resolving lexical competition.

Children with prelingual HL develop language via a degraded auditory signal. These children must therefore cope with two sources of uncertainty when recognizing speech: they must process an auditory signal that is degraded in the moment, and they must compare that input to phonological and lexical representations that are built upon years of degraded input. It is not clear how these jointly contribute to the wait-and-see profile of lexical competition that has been observed in children who use CIs. Investigating these processes in children with more residual hearing (e.g., those who use HAs) may help to clarify this issue.

On the one hand, the sensory and lexical-representation problems may compound, such that a moderate signal degradation combines with poorer representations built up over development to lead to difficulties with spoken word recognition. McMurray et al. (2017) found that prelingually deaf adolescents (ages 12-25 years) with CIs exhibited a wait-and-see profile. This is consistent with earlier work showing that children with CIs as young as 2 years old also show delayed word recognition (Grieco-Calub et al., 2009). Farris-Trimble et al. (2014) used a comparable task to McMurray et al. (2017) and found that *postlingually* deaf adults with CIs showed a sustained competitor activation approach to spoken word recognition. The fact that prelingually and postlingually deaf CI users showed differences in their lexical activation dynamics, despite experiencing what is likely similar in-the-moment degradation, suggests that developing language via a HL may fundamentally alter the listener’s cognitive approach to recognizing words.

On the other hand, the wait-and-see approach may simply be due to poor perceptual acuity. In the studies mentioned above, the listeners who showed wait-and-see also had relatively poor word recognition accuracy in the task. The prelingually deaf CI users averaged 88.5% correct and NH adults listening to 4-channel vocoded speech averaged 81.7% correct, whereas the NH adults listening to a clear signal averaged over 99% correct (McMurray et al., 2017). In contrast, the postlingually deaf CI users and NH adults listening to 8-channel vocoded speech (i.e., those who showed sustained competitor activation) averaged 94.8% and 98.4% accuracy, respectively (Farris-Trimble et al., 2014). Based on this pattern of results, the wait-and-see and sustained competitor activation approaches may simply represent the predictable effects of a lexical system confronted with different degrees of degraded input that is not easily recognizable.

Children who use HAs—who experience less degraded input than listeners with CIs—may help disentangle these hypotheses. In-the-moment signal degradation is reflected by accuracy in the VWP task. A signal that is highly degraded is expected to lead to relatively low accuracy on the VWP (as exemplified by the prelingually deaf CI users in McMurray et al. [2017], who averaged 88.5% correct), whereas high accuracy would indicate good in-the-moment access. On the other hand, the real-time dynamics of spoken word recognition, such as a wait-and-see profile, is likely affected by a combination of in-the-moment signal degradation and *long-term experience* with listening to a degraded signal. If a listener shows both high accuracy and a wait-and-see profile of word recognition, it would suggest that the listener’s wait-and-see profile is due to long-term signal degradation, rather than in-the-moment degradation. Appropriately fit HAs are expected to offer a listener with substantially less signal degradation than CIs. Because of this, coupled with the fact that the VWP task used in the present study was designed to be very easy, it was expected that children with HAs would show high accuracy on the VWP task. Therefore, the real-time word recognition profile shown by the children with HAs (e.g., wait-and-see or sustained competitor activation) could be attributable to long-term signal degradation, rather than degradation in the moment. Including both children with HAs and children with CIs, as well as children with NH, allows for direct group comparison in terms of both accuracy and real-time word recognition profiles.

Spreading Semantic Activation during Spoken Word Recognition

At the broadest level, it is unknown whether differences in higher-level language seen in children with HL may derive from differences in lower-level skills, like word recognition. As a first step in addressing this, we examine semantic processing. Ultimately, a goal of word recognition is to activate the semantics of the speech, so the listener can understand the meaning of what is being said. Thus, one way to examine the downstream consequences of differences in lexical competition resolution is to observe their effects on semantics.

Lexical competition and semantic activation co-occur through a process of cascading activation (Apfelbaum et al., 2011; Moss et al., 1997; Zwitserlood, 1989). Activation of semantic information occurs as soon as any degree of lexical activation has occurred, and lexical competition need not be resolved before semantic activation begins. For example, at the time that a listener has heard *san-*, the word forms of both *sandal* and *sandwich* are active. The listener also activates semantic features of the lexical candidates (e.g., "worn on feet," a semantic feature of *sandal* and "is edible," a semantic feature of *sandwich*).

VWP studies have generally approached this by using items that are semantically related to the target word (e.g., after hearing *sandal*, examining looks to the *foot*). A number of studies have shown that spreading semantic activation is graded based on the degree of semantic overlap between two words (Huettig & Altmann, 2005; Mirman & Magnuson, 2009). This process of cascading activation begins to develop as early as 2 years old (Mani et al., 2012), though the ability to resolve lexical and semantic competition continues to develop throughout childhood (Huang & Snedeker, 2011). The VWP has also confirmed that lexical competition and spreading semantic activation occur in a cascading process, showing, for example, that phonological density affects the time course of fixations to semantically related words (Apfelbaum et al., 2011; Huettig & McQueen, 2007; Yee & Sedivy, 2006). Thus, examining real-time spreading semantic activation can be a useful way to assess the *consequences* of differences in word recognition for downstream processes.

Indeed, signal degradation can affect the extent to which listeners utilize semantic information. Using a VWP task, Sajin and Connine (2014) found that when adults listened to words in background babble, the semantic richness of a word (i.e., the number of semantic features the word had) facilitated fast word recognition more than when listening in quiet. Additionally, van der Feest et al. (2019) used a VWP task to show that for NH adults listening to sentences presented in background noise, semantic context in the carrier sentence only facilitated looks to the target item when the sentence was presented using a clear speaking style; no effect of semantic context was evident when a conversational speaking style was used. When listening in quiet, however, the addition of semantic context increased looks to the target item regardless of the speaking style used. Finally, Nagels et al. (2020) found that when listening to sentences in a VWP task, adults with CIs looked slower but overall more to a semantically related item, relative to listeners with NH. Together, these results indicate that listeners may rely on available semantic information when the auditory signal is degraded, but the extent to which listeners are able to utilize semantics may depend on how difficult the listening conditions are.

Critically, however, this issue has received little attention among populations with early-onset HL. Consequently, it is not clear the degree to which learning language under adverse conditions may affect a listener's real-time ability to access semantic information. One possibility is that effects on semantic processing are completely gated by poor input – that is, poor input delays the resolution of phonological competitors, which in turn alters semantic activation (via this continuous cascade). In this view, children with HL may not have true semantic deficits at all, but instead any differences in spreading semantic activation are simply a product of their poorer word recognition abilities.

However, it is possible that adverse development leads to distinct semantic deficits that cannot be accounted for by phonological-level word recognition. When children with HL develop language via inconsistent auditory input, they may hear words used in fewer semantic contexts than children with NH (Benitez-Barrera et al., 2018). This may lead to weaker semantic connections between words, or between words and their sematic features (Löfkvist et al., 2012; Lund & Dinsmoor, 2016; Wechsler-Kashi et al., 2014). Some studies using picture-word priming tasks have suggested that children with HL may have deficits in their lexical-semantic network organization, though the findings are mixed (de Hoog et al., 2015; Jerger et al., 2002; Jerger et al., 2013). However, these priming studies required children to name words aloud; thus, it is not clear if these semantic deficits extend to speech comprehension, which is arguably a more challenging domain for children with HL.

Thus, an investigation of semantic effects in spoken word recognition could help resolve these questions. Critically, we can ask first if there are semantic processing differences in children with HL. We then ask if these differences are observed after accounting for differences in resolution of phonologically driven lexical competition. A comparison of children using HAs and CIs can help clarify these questions, given the large differences in the quality of the perceptual input experienced by these two groups.

Current Study

To date, research on real-time word recognition in prelingually deaf children with HL has focused on CI users. It remains unknown whether children with HAs adapt lexical access mechanisms in response to learning language via what can be considered a *moderately* degraded signal. It may be the case that developing language via any degree of signal degradation leads to poorly defined phonological representations, causing children with HAs to process speech less incrementally and show a similar wait-and-see approach as prelingually deaf adolescents with CIs (McMurray et al., 2017; Walker, Kessler, et al., 2019). On the other hand, children with HAs may show lexical competition characterized by slightly delayed target word activation with sustained competitor activation (Farris-Trimble et al., 2014). One goal of the present study was to characterize the cognitive mechanisms that children with HAs use to recognize spoken words, in comparison to children with CIs and children with NH. This will inform our theoretical understanding of the effects of in-the-moment versus long-term signal degradation on spoken word recognition, as well as inform our knowledge about potential cognitive mechanisms underlying persistent language difficulties in this clinical population.

Previous research on real-time spoken word recognition in children with HL is additionally limited by sample characteristics. The adolescent CI users in McMurray et al. (2017) represented a wide chronological age range (12-25 years old) and age at implantation range (1.5 to 7.5 years old; mean = 4 years). It is unclear if the findings from McMurray et al. remain applicable to children with severe to profound HL who receive the current standard of audiologic care (CI by age 2 years; Yoshinaga-Itano et al., 2018). It is possible that the wait-and-see profile previously shown by adolescent CI users reflects prolonged early auditory deprivation, rather than developing language via a degraded signal. In this study, we addressed this question by investigating spoken word recognition in children with CIs who were implanted at an early age.

A final goal of the present study was to characterize the time course of spreading semantic activation during spoken word recognition in children with HAs and children with CIs as a way to investigate the downstream consequences of poorer real-time spoken word recognition, and to determine if there are true semantic deficits in children with HL. We examined spreading semantic activation while children with HAs and children with CIs recognized spoken words to clarify the extent to which these children appreciate semantic similarities between words while a speech signal unfolds. We also examined the extent to which differences in the time course of spreading semantic activation are due to differences in lexical access, rather than representing true differences in semantic processing.

METHOD

Participants

Data from 68 children (25 with NH, 24 with HAs, and 19 with CIs) were included in this study. Mean age was 11.0 years ($SD = 0.89$) for the children with NH, 11.0 years ($SD = 0.94$) for the children with HAs, and 10.8 years ($SD = 0.79$) for the children with CIs. Age did not significantly differ between the groups, $F(2,65) = 0.292$, $p = .748$. Females comprised 15 (60%) of the children with NH, 12 (50%) of the children with HAs, and 15 (78.9%) of the children with CIs; the rest were male. Maternal education (based on parent-reported education level) did not differ significantly between groups, $F(2,64) = 0.05$, $p = .95$ (not available for one child with CIs). Table 1 shows demographic and audiologic information about each participant group.

All children with HAs had permanent bilateral sensorineural ($n = 21$) or mixed ($n = 3$) hearing loss and used bilateral behind-the-ear HAs ($n = 23$) or receiver-in-the-canal HAs ($n = 1$). Degree of HL ranged from mild to moderately severe. All children with CIs had permanent bilateral sensorineural hearing loss and used either bilateral CIs ($n = 18$) or a unilateral CI with a contralateral HA ($n = 1$). All children with CIs received a CI by 48 months ($M = 19.8$).

Children were invited to participate in the study if they had at least one caregiver who primarily used spoken English, had vision within normal limits (with correction, if necessary), did not have a diagnosed disability affecting cognition or language (other than HL, if applicable), and were fluent in no languages other than English. Children with HAs and CIs were not invited to participate if the HL was unilateral, the child relied on manual communication in most settings, or HL onset was after 18 months of age[1]. All children were between 9 and 12 years old. To compare children with HL to their closest developmental peers, the NH, HA, and CI groups were matched group-wise based on chronological age (rather than, e.g., vocabulary size or hearing age).

A total of 22 children with CIs participated in the study. Two children with CIs were excluded after testing due to eye disorders (glaucoma, cataract, and/or spontaneous nystagmus) that led to very poor calibration of the eye-tracker. One child with CIs was excluded because of a diagnosis of Autism Spectrum Disorder and because they scored below the normative range on nonverbal cognition. Data from 19 children with CIs were therefore retained in the analyses. No children with NH or HAs were excluded after completing testing.

General Procedure

Several standardized assessments were administered to characterize the listening, language, and cognition skills of the participants in each group. These tasks included a hearing assessment; the Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler & Hsiao-pin, 2011) to assess nonverbal cognition; the Peabody Picture Vocabulary Test, Fourth Edition (PPVT; Dunn & Dunn, 2007) to assess receptive vocabulary; and the Bamford-Kowal-Bench Speech-in-Noise (BKB-SIN) sentence recognition task (Etymotic Research, 2005) to assess speech recognition in noise. The main experimental task was an auditory VWP task, which assessed real-time spoken word recognition. Participants also completed a nonverbal VWP task, which assessed the dynamics of visual processing in the absence of auditory of verbal stimuli. Participants either completed the test battery in a mobile testing unit or in a quiet testing room. All study procedures were approved by the appropriate Institutional Review Board.

Standardized Assessments

Participants were administered the following measures via spoken English by a trained researcher.

Audiological assessment.—Children with HAs completed air conduction threshold testing from 250 to 8000 Hz and bone-conduction thresholds at octave frequencies from 500 to 4000 Hz in both ears. Children with NH completed a hearing screening at 20 dB HL at 500, 1000, 2000, and 4000 Hz at the start of the research visit. They were required to pass in both ears at all frequencies. No children with NH were excluded based on this criterion.

Nonverbal cognition.—Most children (16/19 children with NH, 22/24 children with HAs, and 15/19 children with CIs) completed the Matrix Reasoning subtest of the WASI-II.

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[1] Note that children whose formal diagnosis occurred after 18 months were retained if their audiologist suspected that the HL was present prior to 18 months.

This measure comprises a series of progressively more difficult pattern completion items; children are shown a pattern with a piece missing and must choose the correct piece from five possible alternatives. Children were excluded if they scored 1.5 SD below the normative mean. Nine children did not complete this assessment due to time constraints. Two children with HAs did not complete Matrix Reasoning at the research visit, but they had performed within the normal range on this measure at a previous research visit. For the rest of the children who did not complete Matrix Reasoning, parents reported no concern about the child’s cognitive development. One child with CIs was excluded because he scored more than 1.5 SD below the normative mean.

Receptive vocabulary.—Receptive vocabulary was measured with the PPVT. In this assessment the examiner says a word that describes one of the pictures on a page, and the participant identifies the correct picture. A standard score of 100 represents average performance (SD = 15). PPVT data were not available for one child with NH. PPVT standard scores differed significantly between the groups, $F(2,64) = 11.04$, $p < .001$ (Table 1). Post-hoc comparisons using Tukey’s Honestly Significant Difference (HSD) test showed that children with CIs had significantly lower vocabulary scores than children with NH (M_{NH}=112.5, M_{CI}=93.3, adjusted $p < .001$) and children with HAs (M_{HA}=106.8, adjusted $p = .005$), while the vocabulary scores of children with NH and children with HAs were not significantly different (adjusted $p = .32$).

Speech recognition in noise.—All children completed the BKB-SIN as a measure of speech recognition ability in noise. In this task, participants repeated back sentences presented at 65 dBA from a loudspeaker at 0° azimuth. The sentences were accompanied by four-talker babble that became increasingly louder with each sentence. The outcome measure was the signal-to-noise ratio at which participants would be expected to correctly repeat back 50% of the target words (SNR-50). Accuracy was scored live by a trained experimenter, and participants were asked to repeat themselves if the experimenter was unsure of what a participant said. Participants each completed one list pair for a total of 20 sentences. List pairs were counterbalanced across participants. Sentence repetition in noise differed significantly between the groups, $F(2,65) = 41.76$, $p < .001$ (Table 1). The NH group had significantly lower (i.e., better) SNR-50 scores than the HA and CI groups, and the HA group had significantly lower scores than the CI group (all adjusted p-values < .001).

VWP for Spoken Word Recognition

Design.—We identified word pairs (target + competitor) that captured three types of relationships between the words: cohorts, in which the words began with the same phonemes (e.g., *sandal* and *sandwich*); rhymes, in which the words ended with the same phonemes (e.g., *wizard* and *lizard*); and semantics, in which the two words shared semantic features (e.g., *apple* and *lemon*). There were 30 pairs of each type, leading to 180 words.

Individual trials were constructed using a “pairs-of-pairs” VWP design, similar to Hendrickson, Apfelbaum, et al. (2021). Each trial consisted of the items from two pairs, which were not related to each other. Consequently, depending on the auditory stimulus, one pair served as the target + competitor and the other pair served as two unrelated items.

For example, if *sandal/sandwich* (a cohort pair) was paired with *wizard/lizard* (rhymes), when *sandal* was the auditory stimulus, then *sandwich* was the cohort, and *wizard* and *lizard* served as unrelated items on this cohort trial. However, when *wizard* was the auditory stimulus, then *lizard* was the rhyme, and *sandal* and *sandwich* served as unrelated items on this rhyme trial. This pairs-of-pairs design is efficient as all trials could be included in the analyses (there are no truly unrelated words).

To minimize the role of any unforeseen phonological, semantic, or visual similarities between the pair-of-pairs (as one pair was intended to be unrelated to the other pair), three versions of the four-item sets were created. For example, *wizard* and *lizard* (rhymes) were matched with *trombone* and *guitar* (semantics) in Version A, with *baseball* and *soccer* (semantics) in Version B, and with *market* and *marble* (cohorts) in Version C. Pairs of the same type (e.g., two rhyme pairs) were never matched together, and a given pair was never matched with the same type of pair in all three versions (e.g., a cohort pair was not matched with a rhyme pair in all three versions). Each participant completed either Version A, B, or C (randomly assigned within participant group).

Each trial was either a cohort, rhyme, or semantic trial; only one type of competitor relationship was assessed on each trial. Figure 1 shows an example of visual stimuli and their roles on a cohort trial. Across trials, each word in an item set served as the target twice. This prevented participants from guessing which word would be the target on a given trial by mentally eliminating words that had already served as targets, before hearing the auditory stimulus. Each trial used a unique exemplar of the auditory stimulus so that participants could not utilize idiosyncrasies of a given auditory exemplar to help identify an item on its second presentation. This led to 45 sets (pairs of pairs) × 4 words/set × 2 repetitions for 360 total trials (randomized).

Trial order was randomized for each participant. The spatial locations of the item types were counterbalanced across trials so that each item type (i.e., target, cohort, rhyme, semantically related item, and unrelated items) occurred in each screen location (i.e., top left, top right, bottom left, bottom right) approximately the same number of times for each participant. Presentation of the cohort, rhyme, and semantic trials was interleaved.

Item selection.—Item selection balanced on several factors. First, all items were bisyllabic. In studies of spoken word recognition, cohort effects and semantic priming are robust and easy to detect. However, rhyme effects are smaller and observed less consistently than cohort effects (McQueen & Huettig, 2012). Furthermore, larger rhyme effects are often observed for bisyllabic than monosyllabic words (Hendrickson et al., 2020; Simmons & Magnuson, 2018) and often not observed at all for monosyllabic words (Hendrickson, Apfelbaum, et al., 2021). Thus, to maximize the likelihood of observing rhyme effects, all items were bisyllabic.

Second, all items were in the expected vocabulary of all children in this study. Most items appeared in the Children's Printed Word Database (Masterson et al., 2010), an online database of words in books targeted at children ages 5 to 9. Other items did not appear in the Children's Printed Word Database but were found in the Child Corpus Calculator (Storkel

& Hoover, 2010). Four items did not appear in the Children's Printed Word Database or the Child Corpus Calculator, but close variants of the items did appear in one of these databases (e.g., *sandal* was not found, but *sandals* was found in the Children's Printed Word Database). In these cases, lexical characteristics of the close variant were used. Twelve items were found in neither the Children's Printed Word Database nor the Child Corpus Calculator, but were kept in the study because it was intuitively expected that even 9-year-olds with below-average vocabularies would be familiar with the items. See Supplemental Digital Content, Table S1 for a full list of item pairs and item characteristics.

Semantically related item pairs were primarily drawn from the McRae et al. (2005) database, which provides shared feature norms for word pairs. Possible semantic pairs were excluded if they shared an initial phoneme or had more than one shared phoneme in the same position in both items. Pairs were chosen to represent a variety of semantic categories (e.g., animals, tools, food). To increase the diversity of semantic categories represented in the items, five pairs were drawn from De Deyne et al. (2008) and three were drawn from Vinson and Vigliocco (2008). Both these databases determined semantic similarity based on shared features.

Cohort and rhyme pairs were chosen from similar semantic categories as the items used in the semantic pairs, though phonological competitors never came from the same semantic category. Pairs were chosen so that the two words shared at least three phonemes, except for words that only contained three total phonemes (e.g., *wire*-*fire*). Two-tailed two-sample t-tests indicated that cohort and rhyme pairs did not differ significantly on the average number of shared phonemes per pair, $t(58) = -0.67$, $p = .507$, and cohort pairs had more distinct phonemes per pair on average than rhyme pairs, $t(58) = 5.02$, $p < .00001$ (Table 2).

Table 2 shows lexical frequency and neighborhood density statistics, according to the type of pair (i.e., cohort, rhyme, or semantic). Because lexical frequency is calculated differently in the Children's Printed Word Database and the Child Corpus Calculator, only the words appearing in the Children's Printed Word Database were included in this comparison ($n = 49$ cohort items, $n = 53$ rhyme items, $n = 51$ semantic items). Lexical frequency did not significantly differ across the three competitor types, $F(2,150) = 1.19$, $p = .307$. Neighborhood density was calculated as the number of phonological neighbors in the Children's Printed Word Database. Neighborhood density was significantly different between the three competitor types, $F(2,148) = 24.07$, $p < .001$. Post-hoc comparisons using Tukey's HSD test showed that rhymes had significantly higher density than both cohort (adjusted $p < .001$) and semantic items (adjusted $p < .001$), which did not differ from each other (adjusted $p = .126$).

Visual stimuli.—Visual stimuli were developed with a standard lab protocol (e.g., McMurray et al., 2010). Several images were chosen from a commercial clipart database to represent each word. The images were then viewed and discussed by a focus group of lab members, and the most prototypical depiction of each word was selected by consensus. Each selected image was then edited to remove extraneous details, use a more prototypical color or orientation, and maintain stylistic similarity with other pictures. Care was also taken to minimize the visual similarity of items that would appear together on VWP trials to ensure that looking behavior was driven primarily by phonological overlap and semantic priming, rather than visual similarity. Each final, edited picture was approved by a senior lab member with extensive experience working with the VWP.

Auditory stimuli.—Each target word was recorded at a sampling rate of 44.1 kHz by a native English-speaking female adult with a Midwestern dialect. Words were recorded at the end of a neutral sentence context to ensure consistent intonation across exemplars (e.g., *He said apple*). The speaker included a brief pause before saying each target word to reduce coarticulation. At least five exemplars of each target word were recorded. Exemplars were then digitally extracted from the sentence context, and the best two exemplars for each item were chosen. Exemplars were manually edited to reduce background noise and remove unnecessary clicks, thuds, releases of air, etc., from the recordings. Fifty ms of silence was added to the beginning and end of each recording.

Auditory stimuli in the three types of pairs (cohort, rhyme, and semantic) differed significantly in duration, $F(2,357) = 5.73$, $p = .0036$ (Table 2). Post-hoc comparisons using Tukey's HSD test showed that cohort stimuli duration did not significantly differ from the durations of rhyme or semantic stimuli; semantic stimuli were significantly longer than rhyme stimuli, $p = .002$.

Procedure.—Participants sat in front of a 17" (1280 × 1024 pixel) computer monitor. Before beginning the VWP task, each participant completed a familiarization task so they knew which image would correspond to each target word during the experiment. In this task, each image that would be used during the VWP appeared one-by-one in the center of the computer screen, and the label for each item was written above the image. Participants were instructed to pay attention to the images as the experimenter read the label for each item aloud. For each item, participants were instructed to say "yes" if they knew what the word meant and "no" or "I don't know" if they did not know what the word meant. When participants indicated that they did not know what a word meant, the experimenter gave a short explanation of the word. The experimenter noted which words were unknown to each participant, if any.

Next, participants completed six practice trials to familiarize themselves with the VWP task prior to starting the experiment. Practice trials included auditory and visual stimuli used in the main experiment, but items were not shown in the same sets as in the main experiment. During the practice trials, participants could ask the experimenter to increase or decrease the sound level of the auditory stimuli to achieve a comfortable level.

Participants next began the primary experimental trials. On each trial, a picture was presented in each of the four corners of a computer screen, with a red dot in the center of the screen. Each picture was 300 × 300 pixels and located 50 pixels away from the edge of the screen, vertically and horizontally. After 500 ms, the center dot turned blue, at which time the participant clicked on the dot to initiate the auditory stimulus. Then, the label for one picture was presented at 70 [1] dBA over two speakers positioned directly to the left and right of the computer monitor, and the participant clicked on the corresponding image. Target labels were presented in isolation, without a carrier phrase. Trials were grouped into

10 blocks of 36 trials with a drift correction procedure after every block. Participants were permitted to take a short break between each block. Altogether, this task took approximately 45 minutes to complete.

Nonverbal VWP Task

Participants completed a nonverbal, completely visual analog to the auditory VWP task to estimate the dynamics of visual processing (i.e., overall looking behavior) in the absence of auditory or verbal stimuli. This task was completed immediately after the auditory VWP task, and it included 192 trials, split into 6 blocks of 32 trials. Four pictures of varying shapes and colors appeared on the screen, with one picture per corner. Participants clicked on a blue dot in the center of the screen to initiate each trial. Then, a target shape appeared in the center of the screen for 100 ms. Participants clicked on the picture in a corner that exactly matched the target shape. The four alternatives always included one shape that matched the target in shape and color, one shape that matched the target in color but not shape, and two unrelated shapes that matched the target in neither shape nor color. The two unrelated items were always the same color as each other, so every trial included two pairs of color-matched shapes. This task was similar to that used by Farris-Trimble and McMurray (2013), with the exception that Farris-Trimble and McMurray used basic shapes (e.g., circles and triangles), and the present study used more complex shapes with non-primary colors (e.g., burgundy, lavender) to reduce the possibility of participants internally naming the shapes and colors during the task. The sets of four pictures were presented in a random order for each participant. This task took approximately 15 minutes to complete.

Eye-Tracking Recording and Data Processing

Data Processing.—During both eye-tracking tasks, eye gaze was recorded by an EyeLink 1000 Plus desktop-mounted remote eye-tracker at a sampling rate of 250 Hz. Participants used a chin rest, with height adjusted for comfort. Eye gaze was calibrated using a standard 9-point calibration procedure. Participants completed a drift correction every 36 trials (in the auditory task) or every 32 trials (in the nonverbal task) to account for natural eye drift over time. If participants did not pass the drift correct, the full calibration procedure was repeated.

In the VWP tasks, both eyes were tracked if possible, but only the data from one eye were used for analysis. The eye used for analysis was chosen based on which eye had better calibration and/or more samples available. Both the pupil and corneal reflection were used to determine fixation position.

EyelinkAnal (McMurray, 2019) was used to pre-process the eye-tracking data. During analysis, eye movements were classified as saccades, fixations, and blinks; saccades and subsequent fixations were grouped into a single “look” which began at saccade onset and ended at fixation offset. When determining the item to which a look was directed, the ports of each area of interest (i.e., the locations of the four items on the screen) were increased by

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[1] For a minority of participants, stimuli were presented slightly above or below the default level of 70 dBA due to participant preference. Because the goal was to maximize word recognition by presenting stimuli at a comfortable listening level, small differences in presentation level between participants were not expected to significantly affect results.

100 pixels both horizontally and vertically to account for noise in the eye-tracker. This did not result in any overlap between the four ports.

Data were processed from 0 to 2000 ms. The start of this time window corresponded to the time at which the participant initiated presentation of the auditory stimulus via mouse click. Fixations launched prior to this time window were ignored. Furthermore, eye movements during the first 250 ms of each trial were not analyzed because 1) the first 50 ms of each trial was silence, and 2) it takes about 200 ms to plan and launch an eye movement (Matin et al., 1993). Thus, any eye movements within the first 250 ms of a trial are due to random looking behavior, rather than information in the auditory signal. On trials in which the participant responded before 2000 ms, the location of their final fixation was extended over the rest of the 2000 ms time window. On trials in which the participant had a response time of greater than 2000 ms, eye movements after the 2000 ms mark were ignored.

Trial Exclusions.—VWP trials were excluded from analysis for three reasons: 1) the subject chose the incorrect item, 2) the child did not know a word that appeared in the trial, and 3) the child had an atypically long response time. The VWP is intended to measure the time course of recognizing known words. For this reason, trials containing words that children did not know (either as a target or a competitor) were excluded. A word was considered unfamiliar based on the child’s self-report during the familiarization task. All children were familiar with at least 86% (155/180) of the words. Fourteen children with NH (56% of the group), 14 children with HAs (58.3% of the group), and four children with CIs (21.1% of the group) were familiar with all 180 words. Table 3 shows the mean number of words unknown, by group. Excluding trials with at least one unfamiliar word (on a subject-by-subject basis) led to an average of 7.04 (of 360 trials, $SD = 12.5$) trials excluded for the NH group, 7.67 ($SD = 12.1$) excluded for the HA group, and 43.4 ($SD = 46.2$) for the CI group.

Response time was measured on each VWP trial. The zero timepoint corresponded to the time at which the child initiated the trial via mouse click, which was 50 ms prior to the onset of the auditory stimulus. On some trials, children had particularly long response times, likely due to being off task or inattentive. Trials with a response time of greater than 5 seconds were excluded from analysis. In total, 1.09% of trials were excluded due to long response time (Table 3).

After excluding trials as described above, all further analyses included a mean of 349.2 trials ($SD = 13.1$, range = 298 to 360) for the NH group, a mean of 342.9 trials ($SD = 19.0$, range = 280 to 359) for the HA group, and a mean of 303.0 trials ($SD = 49.9$, range = 183 to 354) for the CI group, out of a total of 360 trials that were presented to each participant. The number of trials differed significantly between groups, $F(2,65) = 14.77$, $p < .001$, driven by the fact that children with CIs had fewer trials than children with NH (adjusted $p < .001$) and children with HAs (adjusted $p < .001$), who did not differ from each other (adjusted $p = .74$). Despite these differences, at least 50% of trials were retained for every child, sufficient for the VWP analyses.

Analyzing Fixation Time Courses.—The proportion of looks to each item type across VWP trials was calculated every 4 ms from 0 to 2000 ms after the onset of the auditory stimulus. This was done for each participant in each trial type (cohort, rhyme, semantic). Looks to the unrelated items were quantified as the mean looks to the two items. We used Bootstrapped Differences of Timeseries (BDOTS; Seedorff et al., 2018) to compare fixation curves across competitor types (e.g., cohort vs. unrelated) and groups. BDOTS takes as input any two sets of timeseries data and determines the periods during which the timeseries significantly differ. The first step in the BDOTS analyses is to fit a curve for each item type, for each participant (details on this curvefitting process below). Next, curves are bootstrapped to obtain confidence intervals. These confidence intervals are then used to compute *t*-tests at every time point (i.e., every 4 ms). The autocorrelation among the resulting *t*-values is computed, and the alpha-value is adjusted based on family-wise error rate. This corrects for multiple comparisons without being as conservative as a traditional Bonferroni approach. Finally, the time periods during which the two curves significantly differed was calculated to determine if and when each group showed significant cohort, rhyme, and semantic effects.

The first step in implementing BDOTS was to fit each participant's fixation curves to a nonlinear function. Logistic models were fit to the curves for target fixations. The logistic curve has four parameters: a *baseline* corresponding to the lower asymptote or minimum looks, a *peak* corresponding to the upper asymptote or maximum looks, a *slope* corresponding to the maximum derivative of the curve, and a *crossover* corresponding to the time at which the slope occurs. Competitor fixation curves (i.e., cohorts, rhymes, semantically related items, and unrelated items) were fit with an asymmetric Gaussian. This function has six free parameters: an *onset baseline* corresponding to the initial asymptote, an *onset slope* corresponding to the rate at which proportion of looks to the item type increases, a *peak* corresponding to the maximum proportion of looks, a *peak location* corresponding to the time at which the *peak* occurs, an *offset slope* corresponding to the rate at which proportion of looks to the item type decreases after the *peak*, and an *offset baseline* corresponding to the final asymptote.

Functions were fit using a constrained gradient descent algorithm that minimizes the least squared error between the function and the data, while obeying reasonable constraints (e.g., the function must be between 0 and 1). Functions were fit using the curvefitting software of McMurray (2020), and these fits were imported into BDOTS for analysis. For the unrelated items, separate curves were fit for the items that were included in cohort, rhyme, and semantic trials. Curvefits for each participant/item-type were compared visually to the participant's corresponding fixation curves to ensure adequate fit. Table 4 provides a summary of the r^2 values representing the match between the fit and the data. The values indicate that the curvefits represented the data well.

For all BDOTs comparisons, any statistically significant findings that occurred within the first 250 ms of the trial were ignored because the first 50 ms of the trial consisted of silence, and it takes approximately 200 ms to plan and launch an eye movement. Therefore, any differences occurring within this early time period represent an artifact of the curvefitting process.

RESULTS

Accuracy and RT on the Auditory VWP

When including only trials in which the child was familiar with all four words, accuracy of the final mouse click was high for all three groups (M_{NH} = 99.1%; M_{HA} = 98.3%; M_{CI} = 97.1%; Table 5). The difference in accuracy between the groups was significant, $F(2,65) = 5.99$, $p = .004$. Children with NH were significantly more accurate than children with CIs (adjusted $p = .003$). The accuracy of children with HAs did not differ significantly from that of children with NH (adjusted $p = .32$) or children with CIs (adjusted $p = .10$). Notably, both the children with HAs and CIs had substantially higher accuracy than has previously been shown by postlingually deaf adults with CIs (94.8%; Farris-Trimble et al., 2014) and prelingually deaf 12- to 25-year olds with CIs (88.5%; McMurray et al., 2017). This validates our assumption that children with HAs would show very high accuracy.

Mean response times on the correct trials (after trial exclusions described in the methods) are shown in Table 5. The three groups of children differed significantly, $F(2,65) = 14.52$, $p < .001$. Post-hoc comparisons showed that children with NH responded significantly faster than children with HAs ($p = .001$) and children with CIs (adjusted $p < .001$), and the response times of children with HAs and children with CIs did not differ significantly (adjusted $p = .23$).

Cohort, Rhyme, and Semantic Effects by Group

Figure 2 shows the time course of fixations to each item type, by group. We first used BDOTS to confirm that participants looked to the meaningful competitors (cohorts, rhymes, and semantically related items) more than the unrelated items (i.e., that participants showed a cohort, rhyme, and semantic effect). Each competitor was compared to the unrelated items that appeared in the corresponding trial types with separate analyses for each hearing group. For each competitor type, all three groups had time periods during which fixations to the competitor were significantly higher than fixations to the unrelated item (Table 6). For all three groups, cohorts tended to be active early (250 ms after trial onset), while rhymes and semantically related items saw significant fixations much later (between 400-600 ms). Once the competitor effect began, the effect was significant until the end, or nearly the end, of the trial. These findings confirmed that the NH, HA, and CI groups each showed significant cohort, rhyme, and semantic effects.

Group Differences in Fixation Time Courses

We next used BDOTS to examine the effect of listener group for each of the competitor types. Because BDOTS can only compare two timeseries, three BDOTS comparisons were conducted to compare the NH and HA groups, the NH and CI groups, and the HA and CI groups. Separate BDOTS analyses were conducted for the target and each competitor type. For the cohorts, rhymes, and semantically related items, we used a difference of differences analysis to control for differences in overall looking (estimated by the unrelated fixations). This asked if the difference between fixations to competitors and the corresponding unrelated items differed between listener groups. Table 7 provides the time periods during which the groups differed for each item type, ignoring the first 250 ms time period. These significant time periods are also denoted by horizontal bars at the top of each panel in Figures 3-6. See Figure S1 of the Supplemental Digital Content for participant-level fixation curves.

Considering the fixation patterns to all item types, both the HA and CI groups show a pattern of spoken word recognition consistent with a wait-and-see profile. Children in both the HA and CI groups were substantially slower to look at the target item relative to the children with NH: as Figure 3a shows, the HA group was delayed by 60.7 ms and the CI group was delayed by 97.7 ms (based on the average crossover parameter for each group). Further, both the HA and CI groups showed reduced cohort fixations, relative to the NH group (Figure 4a), and both the HA and CI groups showed increased fixations to the rhyme relative to the NH group (Figure 5a). The HA and CI groups also showed lower peak fixations to the target relative to the NH group ($M_{NH} = 0.900$, $M_{HA} = 0.846$, $M_{CI} = 0.859$). Together, the fixation patterns in the HA and CI groups are consistent with delayed lexical access and lexical competition, which leads to decreased cohort activation and increased rhyme activation. This pattern is more consistent with a wait-and-see profile than a sustained competitor activation profile because a sustained competitor activation profile would show increased and prolonged fixations to the cohort, rather than reduced and quickly suppressed fixations to the cohort.

Nonetheless, this pattern was somewhat more pronounced in the CI group than the HA group. Children with CIs were slower than the children with HAs to fixate the target (Figure 3b). Moreover, although the CI group was slower to look to the cohort relative to the HA group, peak cohort fixations were similar for the two groups (Figure 4b). Finally, the CI group showed increased rhyme fixations relative to the HA group (Figure 5b). Thus, consistent with their lower accuracy in the task, the CI group seems to show an enhanced wait and see profile relative to the HA group.

When considering looks to the semantically related item, the HA and CI groups both showed delayed and slightly reduced fixations, relative to the NH group (Figure 6a). Although the CI group was slower than the HA group to look to the semantically related item, these two groups showed similar peak semantic fixations (Figure 6b). In the next set of analyses, we examined the extent to which differences in lexical access and competition can explain group differences in semantic fixations.

Spreading Semantic Activation Patterns while Controlling for Lexical Access and Lexical Competition

Semantic activation occurs downstream from phonological word form recognition: a listener cannot access the semantics of a word until they have at least partially activated the corresponding word form. For this reason, slower fixations to a semantically related item may not reflect a distinctly semantic deficit, but rather could derive from the fact that the listener is slower to activate lexical candidates and resolve competition from phonologically related items. We conducted a hierarchical regression to address this. The first level of the model ignored listener group and examined the extent to which variance in speed of fixations to the semantically related item is explained by looks to the target and cohort competitor. The next level of the model then asked whether hearing status explains any additional variance in semantic fixations over and above the variance explained by phonological competition. If hearing status explains additional variance, it would suggest that children with HAs and/or CIs may have underlying differences in real-time spreading semantic activation that cannot be explained by differences in resolving competition among phonological word forms.

To perform this analysis, we needed to collapse the fixation curves into individual estimates that could be used as the dependent or independent variables in the regression (see Supplemental Digital Content, Table S2, for summary statistics and group comparisons of all curvefit parameters). Two aspects of phonological competition (target timing and cohort peak time) were used as the independent variables. We used speed of fixations to the semantically related item as the dependent variable because timing was the aspect of the semantic fixation curves that differed most obviously between the groups. Figure S2 of the Supplemental Digital Content provides diagrams of how the three key variables (target timing, cohort peak time, and semantic timing) were calculated.

To control for differences in the dynamics of lexical (phonological wordform) competition, we identified two key indices. First, speed of lexical access was quantified with a *target timing* variable (McMurray et al., 2019). This was based on the slope and crossover parameters from each participant's target curvefit; these parameters were strongly correlated ($r = -.67$; Figure S2a in the Supplemental Digital Content). The slope and crossover values were combined into a single target timing value because conceptually, both these values should contribute to the overall speed with which the listener looks to the target: a higher slope indicates that the participant is more rapidly moving their gaze toward the target, and an earlier crossover indicates that the participant is initiating their looks toward the target earlier. Target slope and crossover were each log-transformed and converted to Z-scores, based on the available data from all participants. The Z-score for crossover was multiplied by −1 (because a slower response function is indicated by a larger crossover, but a smaller slope). Finally, these two Z-scores were averaged to compute the target timing. A larger target timing value indicated faster looks to the target. See Figure S3 of the Supplemental Digital Content for target fixation curves according to target timing.

Second, lexical competition was quantified using the speed of fixations to the cohort. The *cohort peak time* variable was defined as the time at which the peak fixations to the cohort occurred, based on the double-Gaussian curvefit (Figure S2b in the Supplemental Digital Content).

The *semantic timing* variable quantified the speed at which participants looked to the semantically related item. Our goal was to estimate the timepoint at which spreading semantic activation begins, which was deemed to be more theoretically relevant for the present study than the timepoint at which spreading semantic activation was highest. This information is not straightforward to obtain from the semantic curvefit. Instead, we used a procedure based on McMurray et al. (2008). First, we smoothed the fixations to the semantically related items and unrelated items using a 48 ms triangular window. Next, looks to the unrelated items were subtracted from the looks to the semantically related items for each participant. The difference in looks to the two item types was then normalized for each participant based on the maximum difference in looks. The semantic timing variable was defined as the first time point at which the participant's looks reached 50% of that participant's maximum semantic looks and stayed above the 50% criterion for at least 100 ms (Figure S2c in the Supplemental Digital Content).

Before including the semantic timing variable as the dependent variable in regression analyses, we needed to determine whether this variable was sensitive to the group differences observed in the BDOTS analysis. Because the HA and CI groups showed similar time courses of semantic fixations, these two groups were collapsed into a single group of children with HL. A two-tailed two-sample *t*-test indicated that the HL group (*M* = 675.1 ms, *SD* = 203.4) was 86.4 ms slower to look to the semantically related item than the NH group (*M* = 588.6 ms, *SD* = 147.8), *t*(66) = 1.86, *p* = .068, *d* = 0.486. Although this group difference did not meet the significance threshold of *p* < .05, the semantic timing variable was deemed appropriately sensitive for use in the regression analyses due to the effect size and the a priori hypothesis that semantic timing would be affected by the timing of lexical access and competition.

We examined the contributions of phonological variables (target timing and cohort peak time) and hearing status to the semantic timing variable. We first conducted a linear regression to predict semantic timing from the two phonological variables. In the R environment (R Core Team, 2017) this model was entered as the following using the lm command (1):

$$\text{semantic timing} \sim \text{target timing} + \text{cohort peak time} \qquad (1)$$

On the second level of the model, we added hearing status to determine whether hearing status explained any variance in semantic timing over and above the variance explained by the phonological variables. Groups were dummy coded so that NH = 0 and HL = 1. The second level of the model took the following form (2):

$$\text{semantic timing} \sim \text{target timing} + \text{cohort peak time} + \text{HLvNH} \qquad (2)$$

Table 8 shows the model results. In the first level model, target timing had a significant main effect on semantic timing (*p* = .002): participants who were faster to look to the target also looked faster to the semantically related item, relative to participants who were slower to look to the target. Cohort peak time was not a significant predictor of semantic timing (*p* = .26). Together, target timing and cohort peak time explained 10.5% of the variance in semantic timing.

In the second level model, hearing status (i.e., NH vs. HL) did not explain any additional variance above the variance explained by the phonological variables (*p* = .478). This finding suggests that group differences in looking speed to the semantically related item can primarily be explained by the fact that children with HL are slower to initiate lexical access and resolve lexical competition, rather than by any semantic-specific differences between the groups with NH and HL.

Visual VWP

One concern with the VWP is that differences could derive from more basic differences in decision making (e.g., speed of processing), visual search, or eye-movement control. To rule this out, we used the visual VWP task to determine if children with HL differ from children with NH on these fundamental processes. Data from the visual VWP task were processed similarly to the spoken word task. Looks to targets were fit with the logistic function, and looks to color competitor and unrelated shapes were fit with the asymmetric-Gaussian function (McMurray, 2020). Curvefit parameters were obtained for each model for each participant. Parameters were compared between the NH, HA, and CI groups using one-way ANOVAs. None of the curvefit parameters from the visual VWP task differed significantly between the groups (all p-values > .05; see Supplemental Digital Content, Table S3 and Figure S4), consistent with McMurray et al. (2017). The fact that children with NH, children with HAs, and children with CIs did not significantly differ on the visual VWP task indicates that any differences observed between the groups on the auditory VWP task are due to the auditory/lexical nature of the task, rather than underlying differences in eye movement behavior, visual search, or the dynamics of general decision making.

DISCUSSION

We used a VWP task to characterize the dynamics of lexical competition and spreading semantic activation during spoken word recognition in school-age children with HAs, children with CIs, and children with NH. Relative to the children with NH, both groups of children with HL demonstrated a wait-and-see profile of spoken word recognition, characterized by delayed looks to the target item, reduced looks to the cohort competitor, and increased looks to the rhyme competitor. This wait-and-see profile was more pronounced for the children with CIs than the children with HAs. The children with HAs and children with CIs also showed delayed looks to the semantically related item, an effect that could be attributed to the cascading effects of delayed lexical access.

Effects of HL on Real-Time Lexical Access and Competition

An emerging body of literature using VWP tasks has suggested that when faced with degraded auditory input, listeners tend to show either a *sustained competitor activation* profile or a *wait-and-see* profile (Farris-Trimble et al., 2014; Hendrickson et al., 2020; McMurray et al., 2017; McQueen & Huettig, 2012). These profiles of spoken word recognition have been explained in terms of adaptation to uncertainty: when the listener has a moderate amount of uncertainty in the signal, they are slightly slower to initiate lexical access and are slower to suppress activation of lexical candidates (consistent with sustained competitor activation). When the listener has a high degree of uncertainty in the signal, they instead wait to initiate lexical access until substantially more input has accrued, thus reducing the need for lexical competition (consistent with wait-and-see).

A child with HAs or CIs has two sources of uncertainty when recognizing spoken words. First, the auditory signal they are listening to in-the-moment is degraded due to the child’s HL and hearing device signal processing. Second, the child must map the speech signal onto lexical representations that are built on long-term signal degradation. At the onset of this study, it was unclear whether children with HAs would show a sustained competitor activation profile due to their moderately degraded auditory signal, or a wait-and-see profile due to their early and long-term signal degradation. Because they showed delayed looks to the target, decreased looks to the cohort, and increased looks to the rhyme in the VWP task, the children with HAs in this study showed a profile most consistent with wait-and-see.

We also aimed to characterize the dynamics of spoken word recognition in 9- to 12-year old children with CIs who were implanted at an early age. McMurray et al. (2017) found that 12- to 25-year-old adolescents with CIs showed a wait-and-see profile. In addition to being older than the children in the present study, the participants in the McMurray et al. study had a much later age at implantation ($M = 47.9$ months) than the children in the present study ($M = 19.8$ months). Despite these differences between participant samples, the children with CIs in the current study showed a similar wait-and-see profile to spoken word recognition as the adolescents with CIs in the McMurray et al. study.

The children with HAs and the children with CIs in this study both showed a general pattern of looking behavior consistent with the wait-and-see profile of the CI users of McMurray et al. (2017). However, the results from the children with HL in the present study differ from those of McMurray et al. in important ways. The first difference is the length of delay in target looking. In this study, the children with HAs were 60.7 ms slower to look to the target than the children with NH, and the children with CIs were 97.7 ms slower than the children with NH (based on target crossover). In McMurray et al., the CI users showed a much longer delay of 236 ms. The longer delay in lexical access found by McMurray et al. could be because the participants in that study received their CIs much later than the children in the present study. Prolonged auditory deprivation early in life may permanently affect the speed and/or efficiency with which listeners can recognize spoken words later in life.

The difference in target delay between the children with HL in this study and the CI users from McMurray et al. (2017) was unexpected, given the fact that the participants with HL in both studies showed decreased looks to the cohort. It was previously believed that the decreased lexical competition seen in the wait-and-see profile is a direct consequence of substantially delayed target word activation. However, the present findings indicate that decreased competition can occur even when the delay in target word activation is relatively small. This suggests that decreased lexical competition is a specific cognitive adaptation to uncertainty, rather than being solely the natural result of slow lexical access. Indeed, the postlingually deaf adult CI users in Farris-Trimble et al. (2014) were 74 ms slower to initiate lexical access than the adults with NH, but they did not show decreased lexical competition.

Notably, the children with HL in this study were highly accurate at recognizing words in the VWP task, with an average of 98.3% accuracy for the HA group and 97.1% for the CI group. Both groups were substantially more accurate than the prelingually deaf CI users ($M = 88.5\%$) in McMurray et al. (2017). Accuracy is generally not emphasized as a metric of performance in the VWP. However, VWP accuracy is important to consider in conjunction with the VWP time course data because accuracy can be considered as a measure of in-the-moment input quality, analogous to the kind of clinical measures that assess word recognition accuracy in quiet for the same purposes. With their high overall accuracy, it is clear that the VWP task used in this study was quite easy for both the children with HAs and children with CIs. The CI users in McMurray et al., on the other hand, were less certain about the auditory input, even on the trials in which they selected the correct picture. The difference in overall accuracy between participants with HL in the present study and the CI users in McMurray et al., coupled with the fact that word recognition was less delayed for participants in the present study, suggests that part of the delay in lexical access shown by listeners with HL across studies is partly due to in-the-moment encoding quality.

Importantly, that is not the whole story. The fact that children with HL showed a wait-and-see profile of spoken word recognition despite having good in-the-moment access to the auditory input suggests that long-term experience of uncertainty can also play a role in spoken language processing, even if the signal is clear in the moment. Previous research has shown a wait-and-see profile when NH listeners process highly degraded speech (i.e., 4-channel vocoded speech or very soft speech) or when prelingually deaf CI users listen to speech (Hendrickson et al., 2020; McMurray et al., 2017). Importantly, NH listeners do not show wait-and-see when listening to moderately degraded speech (8-channel vocoded speech or slightly soft speech): they only show this pattern when listening in highly uncertain situations (81.7% accuracy with 4-channel vocoded speech), or when they must adapt quickly to a novel stimulus (98.8% to 99.1% accuracy with 40 dBA speech). To our knowledge, this is the first study to show a wait-and-see profile in listeners who are highly accurate while listening to speech *as they normally hear it*. The findings indicate that although some listeners may utilize a wait-and-see profile to cope with in-the-moment signal degradation, for the children with HL in this study, this was not the case. Rather, wait-and-see can also be the result of long-term developmental experience with degraded input. As such, this profile fundamentally represents a cognitive strategy that listeners may utilize regardless of the quality of the input in-the-moment.

As a whole, this suggests that that the wait-and-see profile shown by the children with HL in this study is not likely due to their in-the-moment uncertainty, but rather is likely due to their long-term degraded auditory input. Children who learn spoken language via any degree of HL must develop phonological representations while coping with multiple sources of inconsistent auditory access. Many children do not use their hearing devices full time (Walker et al., 2015; Wiseman & Warner-Czyz, 2018), and all hearing devices degrade the auditory signal to a certain extent (e.g., due to limited bandwidth and spectral degradation; Moeller & Tomblin, 2015; Stelmachowicz et al., 2001). This prolonged inconsistency, even if relatively mild, may lead to permanent differences in how children with HL mentally represent sounds and words: these mental templates for speech sound categories have been proposed to be underspecified relative to children who develop language via a consistently clear signal (AuBuchon et al., 2015; McMurray et al., 2017; Pisoni et al., 2008; Wechsler-Kashi et al., 2014). In this study, children with HAs and children with CIs showed similar overall profiles of spoken word recognition in the VWP task, despite the fact that CIs typically provide the listener with a much more degraded signal than HAs. These findings suggest that these children's long-term experience with auditory uncertainty, rather than solely their in-the-moment input degradation, is responsible for their wait-and-see approach to spoken word recognition. In other words, the wait-and-see profile of children with early-onset HL is not (only) a strategy they adopt to deal with speech that is difficult to understand in that moment, but rather a long-term strategy they have adopted in dealing with a lifetime of auditory uncertainty.

Although the children with HAs and children with CIs in this study showed similar dynamics of spoken word recognition in the VWP task, the children with CIs showed a more exaggerated wait-and-see profile than the children with HAs. Relative to the children with HAs, the children with CIs showed slower looks to the target, decreased looks to the cohort, increased looks to the rhyme, and slower looks to the semantically related item in the VWP task. Thus, although the two HL groups showed qualitatively similar profiles of spoken word recognition, they were quantitatively different. It is possible that the higher signal degradation provided by a CI than a HA causes a more extreme wait-and-see profile. It is also possible that differences between the HA and CI groups in terms of language skills, such as vocabulary, are responsible for the differences between these groups. In this study, the children with CIs had vocabulary scores that were on average one standard deviation lower than the children with HAs. Previous work has shown that vocabulary influences children’s word recognition skills, including in VWP and other experimental paradigms (Borovsky & Peters, 2019; Evans et al., 2018; Klein et al., 2017; Law et al., 2017; Walker, Kessler, et al., 2019).

Effects of HL on Real-Time Spreading Semantic Activation

All three groups of children showed higher looks to the semantically related item than the unrelated item. This finding suggests that like the children with NH, the children with HAs and children with CIs showed spreading semantic activation from the target word as they were hearing it, causing activation of semantically related words. This finding is consistent with recent work showing that children with HAs and children with CIs use semantic information to facilitate spoken word recognition (Blomquist et al., 2021; Holt et al., 2021; Simeon & Grieco-Calub, 2021; Walker, Kessler, et al., 2019).

Compared to children with NH, the children with HAs and children with CIs were slower to look to the semantically related item. This is likely indicative of delays in spreading semantic activation. However, a delay in spreading semantic activation during spoken word recognition can be a downstream effect of delayed lexical access. Through the process of cascading activation, the listener does not access the semantics of a word until after the word form has been at least partially activated in the mental lexicon (Apfelbaum et al., 2011; Moss et al., 1997; Zwitserlood, 1989). Relative to children with NH, the mean semantic delays for the HL groups (75.2 ms for the HA group and 100.6 ms for the CI group, based on the semantic timing variable) were similar to the mean lexical access delays (60.7 ms for the HA group and 97.7 ms for the CI group, based on target crossover). When considering all children, the time at which participants looked at the semantically related item (i.e., the semantic timing variable) was directly associated with how quickly participants looked at the target (Table 8). Importantly, hearing status did not explain any additional variance in semantic timing. This suggests that the delay shown by children with HL in looking to the semantically related item was due to different speeds of lexical access, rather than hearing status per se.

On the one hand, it is encouraging that hearing status did not explain unique variance in semantic timing. Based on the analyses in the present study, there is no evidence for weaker semantic connections between words in the mental lexicon of children with HAs or children with CIs. Previous research has suggested children with HL may have weaker semantic connections between words (Jerger et al., 2002; Walker, Redfern, et al., 2019), though past findings have been mixed (de Hoog et al., 2015; Jerger et al., 2013). It is possible that some children with HL do experience deficits in the quality of certain aspects of their lexical-semantic networks due to their HL. For example, the children with CIs in the present study (but not the children with HAs) had fewer words in their mental lexicons than the children with NH, as indicated by lower receptive vocabulary scores. However, based on the results from the VWP task in this study, there was no evidence of weakened *connections* between known words among the children with HL.

On the other hand, the children with HL did show a delay in looks to the semantically related item, and this delay can be attributed to differences in speed of lexical access. The findings support the idea that the wait-and-see dynamics of resolving word form competition directly affects access to word meaning as a continuous cascade.

In everyday listening situations, listeners must access word meaning quickly, or risk falling behind in terms of understanding what is being said (Nation, 2014). Even children with minimal HL show deficits in discourse comprehension, even when they are highly accurate at repeating back spoken sentences (Griffin et al., 2020; Lewis et al., 2015). It is possible that the relatively small delay in spreading semantic activation at the single-word level builds up during connected speech, as words are uttered sequentially. This may cause the listener to fall behind and fail to retain the meaning of what was said. Concluding that a direct link exists between the real-time dynamics of individual word recognition and functional understanding of real-world discourse is beyond the scope of this study. However, future research should examine the potential role of these single-word processing mechanisms during more complex comprehension tasks, especially among children with HL. Critically, our work illustrates how a small deficit in low level skills can cascade to create higher level impairments, even if higher level skills are intact.

Clinical Implications

Although children with HAs and children with CIs achieved high word recognition accuracy on the VWP task, they showed different patterns of lexical access, lexical competition, and spreading semantic activation than the children with NH. This suggests that even when children with HL perform well on clinical speech recognition tasks, we cannot assume that they are processing speech as quickly or efficiently as children with NH. To ensure the best possible access to speech, children with HL should continue receiving classroom accommodations, such as remote microphone technology, as they progress through middle and high school. Future work should examine the degree to which these accommodations offer gains in speech recognition efficiency, not just accuracy.

The findings of this study have implications for clinical intervention approaches for children with HL. The fact that the delay in spreading semantic activation in children with HL was due to delayed lexical access, rather than being a semantic-specific delay, suggests that intervention targeting lexical access speed may in turn speed up semantic activation. In other words, helping children with HL to recognize words faster should help them to understand the meanings of those words more automatically. Kapnoula and McMurray (2016) showed that when adult listeners were required to attend to small phonological differences between words during training tasks, they were better able to resolve in-the-moment lexical competition. This suggests that the dynamics of real-time spoken word recognition processes are amenable to intervention. Further research is needed to understand the effects of word recognition training on the listening comprehension skills of children with HL.

Limitations and Future Directions

One limitation of this study is the generalizability of the results, due to participant characteristics. All participants were required to be native English speakers and have no disabilities known to affect language or cognitive skills. Children with HL were required to have HL onset prior to 18 months old and rely primarily on spoken language. These inclusion criteria resulted in relatively homogenous participant groups. Furthermore, the participants in this study represented a socioeconomically advantaged group. Of the 42 children with HAs or CIs for whom parent education data were available, all but two (95.2%) had a mother who attended college and 29 (69.0%) had a mother with at least a bachelor’s degree. For these reasons, we cannot generalize the findings of this study to children with more diverse language and cognitive abilities, auditory experience, and socioeconomic backgrounds.

In this study, auditory stimuli consisted of only single words. In everyday life, however, children must be able to process and understand multi-word sentences and multi-sentence discourse. It is possible that the relatively small delay in lexical access shown by children with HL at the single-word level compounds into an even greater delay when these children are listening to multi-word utterances (but see Smith & McMurray, 2022, for evidence against this hypothesis in postlingually deaf adults with CIs). On the other hand, most sentences contain semantic and syntactic cues that help the listener predict upcoming words or fill in the blanks of words and sounds that were missed. Children with HL might use these sentential cues to avoid falling further behind children with NH while listening to sentences. Future research should investigate the spoken word recognition dynamics of children with HL while recognizing full sentences to better understand how these children recognize words under more realistic conditions.

Another limitation is that although the three participant groups were matched on chronological age, they were not matched on language abilities. Receptive vocabulary scores did not differ significantly between the NH group and the HA group, but the CI group had significantly lower receptive vocabulary scores than the other two groups (though the CI group’s mean PPVT score of 93.3 was still within the normative range of the assessment). In younger children with NH, vocabulary predicts the time course of spoken word recognition (e.g., Borovsky & Peters, 2019; Law et al., 2017). However, little is known about how vocabulary influences the real-time word recognition skills of children with HL. It is possible that in this study, the group differences in the time course of lexical access and spreading semantic activation are partially due to differences in language skills, rather than hearing status, especially when comparing the CI and NH groups. Language skills are unlikely to fully account for the group differences, however, because the NH and HA groups were relatively well-matched on vocabulary scores and still showed substantial differences in their time courses of word recognition. Further research is needed to tease apart the factors affecting the dynamics of spoken word recognition in children with a range of hearing abilities, especially the relative contributions of auditory access and vocabulary.

Finally, it is unclear from this study whether the differences in spoken word recognition between children with NH and children with HL should be considered a deficit or simply a difference. It is possible that the wait-and-see profile shown by children with HL represents an adaptive strategy for coping with uncertainty. If children with HL have difficulty recognizing individual speech sounds due to fuzzy phonological templates or noise in the auditory signal, the most effective approach to recognizing the word may indeed be to wait until additional input arrives before activating lexical candidates. In this case, faster lexical access may actually impede word recognition and speech understanding if the listener over-activates lexical candidates that are inconsistent with the speech signal. Examining the association between real-time dynamics of spoken word recognition and children's ability to retain meaning from speech would provide insight into the extent to which the wait-and-see profile of children with HL represents an effective adaptation or a speech processing deficit.

Conclusion

This study used a VWP task to examine the dynamics of lexical access, lexical competition, and spreading semantic activation during spoken word recognition in school-age children with and without HL. Consistent with a wait-and-see profile of spoken word recognition, both children with HAs and children with CIs showed slower real-time lexical access and reduced lexical competition while recognizing spoken words, relative to children with NH. This wait-and-see profile was more pronounced among the children with CIs than the children with HAs. Across groups, the delay in lexical access directly led to a delay in activating the semantics of the target word. Despite having access to auditory signals with very different degrees of degradation, the children with HAs and children with CIs showed remarkably similar profiles of real-time spoken word recognition. The findings indicate that developing language via inconsistent or degraded input can permanently alter the dynamics of spoken word recognition, even when a listener has high certainty about the in-the-moment auditory signal. These findings provide insight into the mechanisms that may underlie the persistent spoken language deficits seen in children with any degree of HL.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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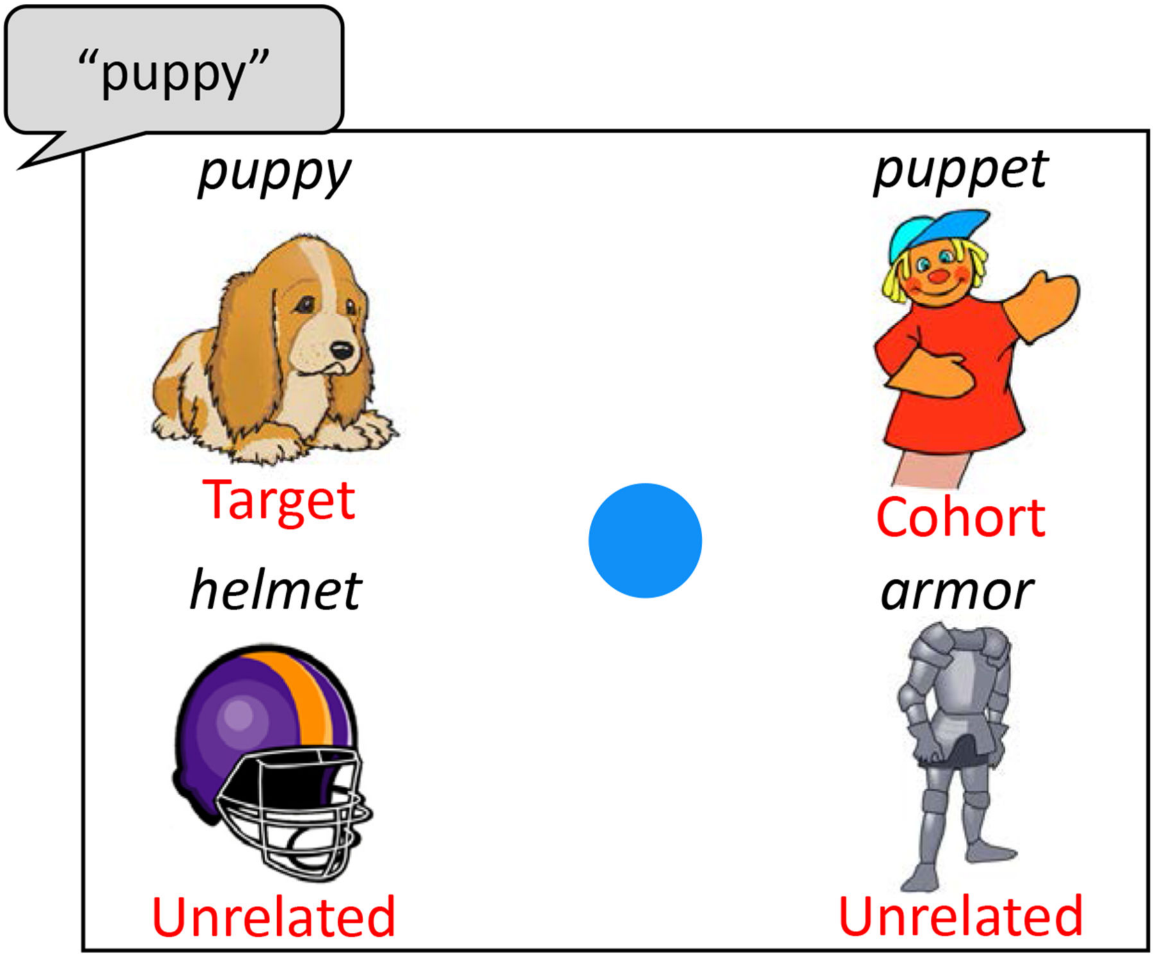

Figure 1.
Example of visual stimuli and their relative roles on one VWP trial. Grey speech bubble indicates the auditory stimulus (i.e., the target word). Italicized words indicate picture labels, and red words indicate the role the item plays in the trial. Note that no written words were actually present on the screen during the VWP task.

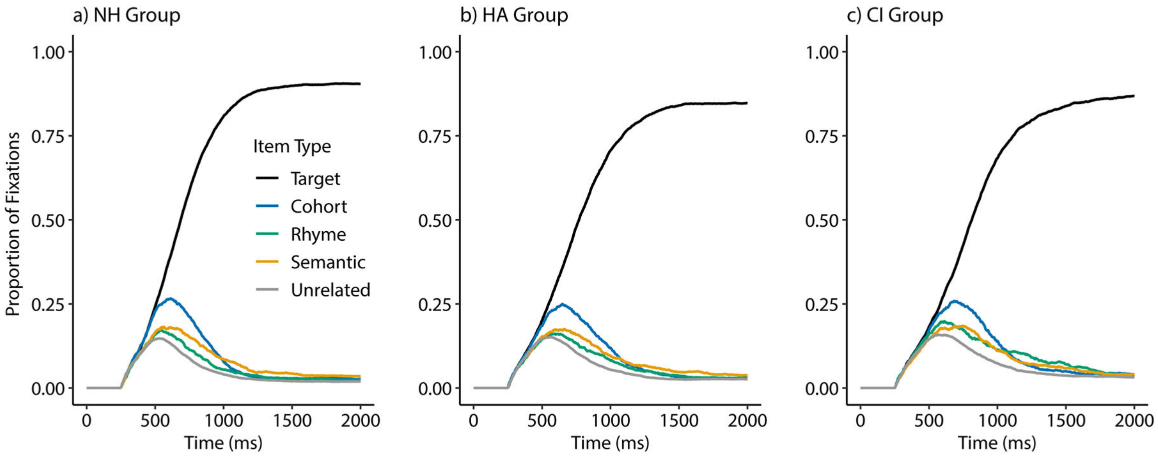

Figure 2.

Time courses of fixations to each item type for the a) normal hearing (NH) group, b) hearing aid (HA) group, and c) cochlear implant (CI) group, averaged across trials. Data are pooled across all three trial-types. Trial onset corresponds to 0 ms. Note that fixations during the first 250 ms after stimulus onset are set to 0 because trials began with 50 ms of silence, and eye movements take 200 ms to plan and launch.

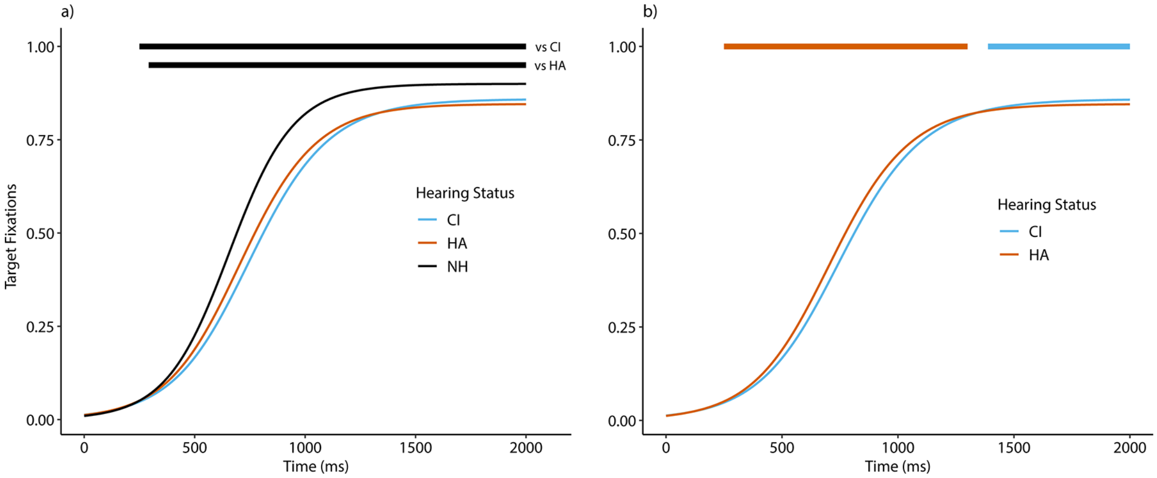

Figure 3.

Time courses of group average curvefits for target fixations. Horizontal bars at the top of each panel indicate the time periods during which groups differ significantly based on BDOTS analyses. The color of the horizontal significance bars indicates which group had higher proportion of fixations. Panel a) shows the comparisons between the normal hearing (NH) group and each group with hearing loss, and panel b) shows the comparison between the cochlear implant (CI) group and the hearing aid (HA) group.

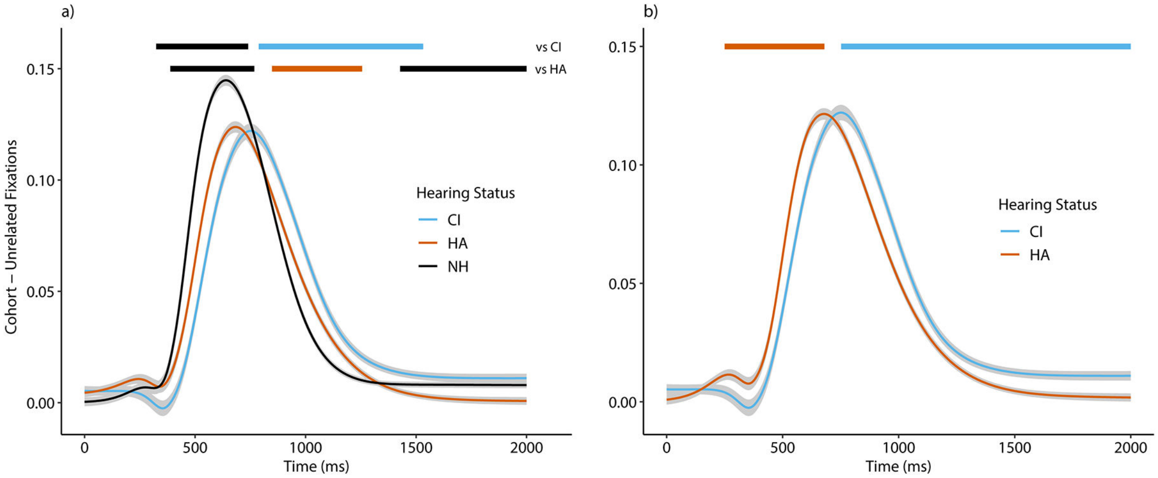

Figure 4.

Time courses of group average curvefits for cohort fixations, minus curvefits for fixations to unrelated items in cohort trials. Horizontal bars at the top of each panel indicate the time periods during which groups differ significantly based on BDOTs analyses. The color of the horizontal significance bars indicates which group had higher proportion of fixations. Grey regions indicate 95% confidence intervals. Panel a) shows the comparisons between the normal hearing (NH) group and each group with hearing loss, and panel b) shows the comparison between the cochlear implant (CI) group and the hearing aid (HA) group.

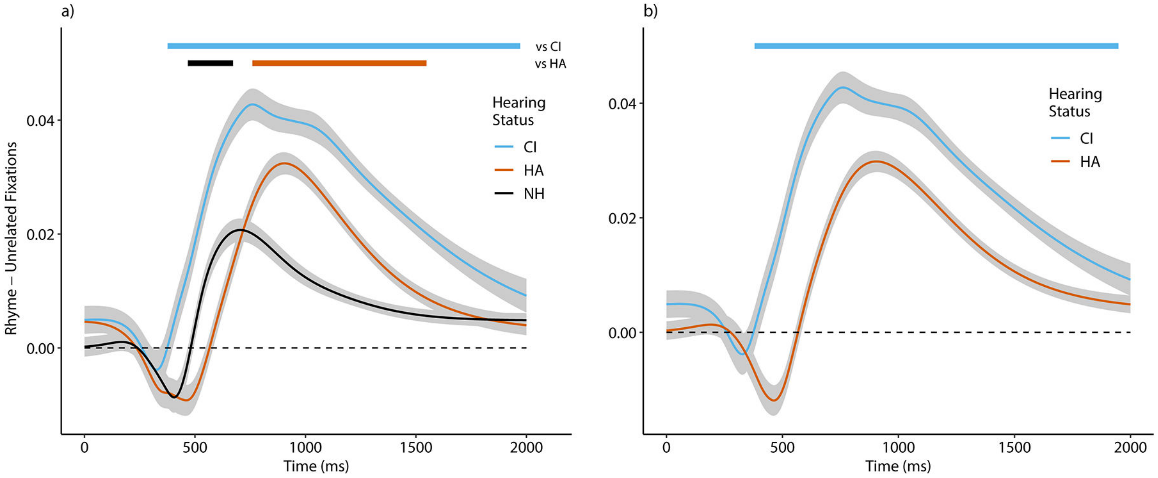

Figure 5.

Time courses of group average curvefits for rhyme fixations, minus curvefits for fixations to unrelated items in rhyme trials. Horizontal bars at the top of each panel indicate the time periods during which groups differ significantly based on BDOTs analyses. The color of the horizontal significance bars indicates which group had higher proportion of fixations. Grey regions indicate 95% confidence intervals. Dashed line indicates y = 0. Panel a) shows the comparisons between the normal hearing (NH) group and each group with hearing loss, and panel b) shows the comparison between the cochlear implant (CI) group and the hearing aid (HA) group.

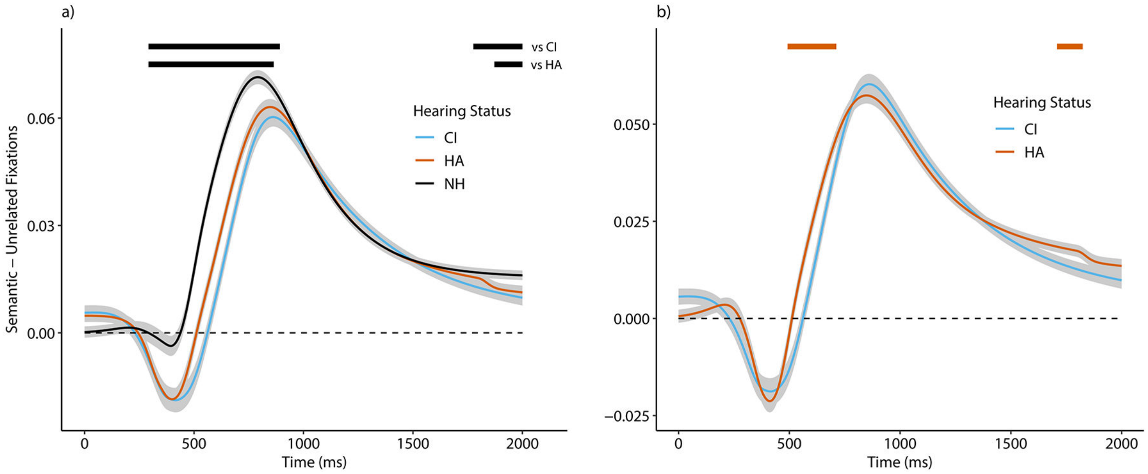

Figure 6.

Time courses of group average curvefits for fixations to semantically related items, minus curvefits for fixations to unrelated items in semantic trials. Horizontal bars at the top of each panel indicate the time periods during which groups differ significantly based on BDOTs analyses. The color of the horizontal significance bars indicates which group had higher proportion of fixations. Grey regions indicate 95% confidence intervals. Dashed line indicates y = 0. Panel a) shows the comparisons between the normal hearing (NH) group and each group with hearing loss, and panel b) shows the comparison between the cochlear implant (CI) group and the hearing aid (HA) group.

Table 1.

Demographic characteristics of each participant group

Variable	NH Group (n = 25)	HA Group (n = 24)	CI Group (n = 19)
Age (years)	11.0 (0.89)	11.0 (0.94)	10.8 (0.79)
Sex (% female)	60%	50%	78.9%
Maternal Education (years)	16.0 (2.15)	16.3 (2.29)	16.1 (2.70)
Age at HL Identification (months)	-	2.04 (9.79)	4.95 (9.63)
Age at 1st HA (months)	-	6.02 (9.49)	7.63 (7.41)
Age at 1st CI (months)	-	-	19.8 (11.6)
Better-Ear Unaided PTA (dB HL)	< 20	48.9 (9.90)	-
PPVT Standard Score	112.5 (13.7)	106.8 (12.6)	93.3 (14.2)
BKB-SIN SNR-50	−2.88 (2.14)	0.12 (2.52)	4.29 (3.13)

Note: Values are entered as *M* (*SD*), unless otherwise specified. Maternal education was not available for one child with CIs. NH = normal hearing, HA = hearing aid, CI = cochlear implant, HL = hearing loss, PTA = pure-tone average, PPVT = Peabody Picture Vocabulary Test, BKB-SIN = Bamford-Kowal-Bench Speech-in-Noise Test, SNR = signal-to-noise ratio.

Table 2.

Item characteristics by competitor type

		Cohort	Rhyme	Semantic	Test Statistic	*p*
Lexical Frequency	M	81.43	68.70	50.82	$F = 1.19$	0.307
	SD	121.74	80.32	94.25		
Neighborhood Density	M	2.21	4.68	1.16	$F = 24.07$	< .001
	SD	2.44	3.52	1.53		
Shared Phonemes/Pair	M	3.10	3.20	-	$t = -0.67$	0.507
	SD	0.48	0.66	-		
Distinct Phonemes/Pair	M	1.75	1.10	-	$t = 5.02$	< .00001
	SD	0.67	0.24	-		
Stimulus Duration (ms)	M	529.9	504.1	549.6	$F = 5.73$	< .01
	SD	111.3	89.2	110.9		

Note: Lexical frequency (frequency/million) and neighborhood density were calculated based on the Children’s Printed Word Database (Masterson et al., 2010).

Table 3.

Number of words and trials excluded in the auditory visual world paradigm task

		NH Group	**HA Group**	**CI Group**	***F* Statistic**	***p*-value**
Number of Words Unfamiliar	M	0.92	1.00	6.00	11.93	<.001
	SD	1.73	1.59	6.74		
	Range	0-8	0-5	0-25		
Number of Trials with Response Time > 5 seconds	M	1.12	4.33	7.05	2.77	.07
	SD	1.48	10.1	10.9		
	Range	0-5	0-45	0-45		

Note: NH = normal hearing, HA = hearing aid, CI = cochlear implant

Table 4.

Curvefit r^2 values for each type of item in the visual world paradigm task

Item Type	Mean	Standard Deviation	Minimum	Maximum
Target	.997	.001	.991	.999
Cohort	.972	.020	.870	.993
Rhyme	.938	.039	.769	.984
Semantic	.945	.037	.769	.984
Unrelated (Cohort)	.961	.025	.880	.989
Unrelated (Rhyme)	.969	.019	.869	.991
Unrelated (Semantic)	.968	.018	.903	.992

Note: Looks to unrelated items were fit according to the trial type they appeared in, indicated by words in parentheses.

Table 5.

Characteristics of performance on the auditory visual world paradigm task

		NH Group	**HA Group**	**CI Group**	***F* Statistic**	***p*-value**
Accuracy	M	99.1%	98.3%	97.1%	5.99	.004
	SD	0.67%	1.34%	3.35%		
	Range	97.2-100%	95.3-100%	87.2-100%		
Response Time (ms)	M	1509.0	1734.0	1842.5	14.52	<.001
	SD	171.8	220.6	246.1		
	Range	1255-1882	1363-2402	1431-2439		

Note: NH = normal hearing, HA = hearing aid, CI = cochlear implant

Table 6.

Time periods during which fixations to meaningful competitors differed significantly from fixations to unrelated items, based on Bootstrapped Differences of Timeseries.

Subject Group	Trial Type	Autocorrelation	Adjusted Alpha	Direction of Effect	Time Period of Significant Difference (ms)
NH Group	Cohort	.9843	.0009	Cohort > Unrelated	**250-2000**
	Rhyme	.9911	.0015	Unrelated > Rhyme	332-456
				Rhyme > Unrelated	**504-2000**
	Semantic	.9911	.0015	Semantic > Unrelated	**460-2000**
HA Group	Cohort	.986	.001	Cohort > Unrelated	**250-1696**
	Rhyme	.9907	.0015	Unrelated > Rhyme	352-540
				Rhyme > Unrelated	**592-2000**
	Semantic	.9896	.0014	Unrelated > Semantic	308-496
				Semantic > Unrelated	**528-2000**
CI Group	Cohort	.9843	.0010	Cohort > Unrelated	**250-2000**
	Rhyme	.9935	.0022	Rhyme > Unrelated	**428-2000**
	Semantic	.9888	.0013	Unrelated > Semantic	312-544
				Semantic > Unrelated	**584-2000**

Note: Bold values indicate the time periods of the main cohort, rhyme, and semantic effects for each group. Any statistically significant differences occurring within the first 250 ms were ignored because they represented an artifact of the curvefitting process, rather than any meaningful difference in fixations. NH = normal hearing, HA = hearing aid, CI = cochlear implant

Table 7.

Time windows during which the curvefits for normal hearing (NH), hearing aid (HA), and cochlear implant (CI) groups differ significantly, based on Bootstrapped Differences of Timeseries

Comparison	Autocorrelation	Adjusted Alpha	Direction of Effect	Time Period of Significant Difference (ms)
Target				
NH vs HA	0.9929	.0020	NH > HA	292-2000
NH vs CI	.9916	.0017	NH > CI	250-2000
HA vs CI	.9896	.0014	HA > CI	250-1300
			CI > HA	1388-2000
Cohort				
NH vs HA	.9807	.0008	NH > HA	388-768
			HA > NH	848-1256
			NH > HA	1428-2000
NH vs CI	.9776	.0007	NH > CI	324-740
			CI > NH	788-1532
HA vs CI	.985	.001	HA > CI	250-680
			CI > HA	752-2000
Rhyme				
NH vs HA	.9829	.0009	NH > HA	468-672
			HA > NH	760-1548
NH vs CI	.9903	.0015	CI > NH	376-1972
HA vs CI	.9874	.0012	CI > HA	380-1948
Semantic				
NH vs HA	.9824	.0008	NH > HA	292-864
			NH > HA	1872-2000
NH vs CI	.9799	.0008	NH > CI	292-892
			NH > CI	1776-2000
HA vs CI	.9805	.0008	HA > CI	492-712
			HA > CI	1708-1824

Note: Any statistically significant differences occurring within the first 250 ms were ignored because they represented an artifact of the curvefitting process, rather than any meaningful difference in fixations.

Table 8.

Effects of phonological variables and hearing status on semantic timing

Level 1: $r^2 = .105$, $F(2,65) = 3.81$, $p = .027$				
Variable	**Estimate**	**Standard Error**	***t*-value**	***p*-value**
Intercept	783.5	185.0	4.26	< .001
Target Timing	−69.4	25.1	−2.76	.008
Cohort Peak Time	−0.224	0.292	−0.767	.446
Level 2: $r^2 = .112$, $F(3,64) = 2.69$, $p = .054$				
Variable	**Estimate**	**Standard Error**	***t*-value**	***p*-value**
Intercept	792.8	185.1	4.28	< .001
Target Timing	−58.7	29.3	−2.00	.049
Cohort Peak Time	−0.280	0.303	−0.923	.359
Hearing Status	40.8	57.2	0.713	.478
Difference between levels: r^2 change = .007, $F(1,64) = 0.509$, $p = .478$				