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Research Article

Children With Cochlear Implants Use Semantic Prediction to Facilitate Spoken Word Recognition

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Purpose: Children with cochlear implants (CIs) are more likely to struggle with spoken language than their age-matched peers with normal hearing (NH), and new language processing literature suggests that these challenges may be linked to delays in spoken word recognition. The purpose of this study was to investigate whether children with CIs use language knowledge via semantic prediction to facilitate recognition of upcoming words and help compensate for uncertainties in the acoustic signal.
Method: Five- to 10-year-old children with CIs heard sentences with an informative verb (*draws*) or a neutral verb (*gets*) preceding a target word (*picture*). The target referent was presented on a screen, along with a phonologically similar competitor (*pickle*). Children's eye gaze was recorded to quantify efficiency of access of the target word and suppression of phonological competition. Performance was compared to both an age-matched group and vocabulary-matched group of children with NH.
Results: Children with CIs, like their peers with NH, demonstrated use of informative verbs to look more quickly to the target word and look less to the phonological competitor. However, children with CIs demonstrated less efficient use of semantic cues relative to their peers with NH, even when matched for vocabulary ability.
Conclusions: Children with CIs use semantic prediction to facilitate spoken word recognition but do so to a lesser extent than children with NH. Children with CIs experience challenges in predictive spoken language processing above and beyond limitations from delayed vocabulary development. Children with CIs with better vocabulary ability demonstrate more efficient use of lexical-semantic cues. Clinical interventions focusing on building knowledge of words and their associations may support efficiency of spoken language processing for children with CIs.
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Cochlear implants (CIs) have transformed the lives of children born deaf. While these devices enable individuals to hear via electrical stimulation of the auditory nerve, the signal they provide is degraded, making speech perception and language comprehension more difficult. Research has shown that children with CIs continue to perform more poorly than their peers with normal hearing (NH) on almost every aspect of speech and language (Nittrouer & Caldwell-Tarr, 2016). Children with CIs are likely to be delayed in language acquisition relative to their peers with NH, although there is a great deal of individual variability, with some children with CIs performing within or even above the average range of language abilities for their age.

While language ability of children with CIs has typically been investigated via assessment of language knowledge (e.g., vocabulary, morphosyntax), language ability can also be characterized as the capacity to process language input in real time, otherwise known as *language processing*. Language processing involves parsing the speech signal to access word meanings and construct an overall meaning of the utterance being perceived. In order to efficiently process the incoming speech stream, listeners with NH utilize what they know about words to predict both the word they are currently perceiving (Sekerina & Brooks, 2007; Swingley et al., 1999) and upcoming words in the sentence (Borovsky et al., 2012; Mani & Huettig, 2012; Nation et al., 2003).

There is limited research into how children with CIs process language in real time and whether they use prediction to facilitate spoken language comprehension. Since children with CIs are perceiving and attempting to parse a

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degraded speech signal, the use of prediction may help to compensate for uncertainty in the bottom-up acoustic signal. On the other hand, prediction may be hindered by limited language knowledge or uncertainty about the acoustic signal. Studies of language processing using real-time paradigms such as eye tracking allow us to investigate whether children are able to use their language knowledge to more efficiently parse the degraded speech signal to understand language in real time. Better understanding of how children with CIs process language could help illuminate the mechanisms underlying the language delays observed in this population, which could result in better targeted intervention strategies for individual children with CIs. In the next sections, we will discuss what is known about spoken word recognition and word-level prediction in children with CIs, followed by discussion of sentence-level prediction.

Spoken Word Recognition

Listeners with NH from toddlerhood to adulthood utilize immediate prediction to make recognition of spoken words more efficient (Allopenna et al., 1998; Swingley et al., 1999). They use early-arriving phonemes (e.g., *sand–*) in a spoken word to consider a set of words that match the available acoustic input, and as the word unfolds across time, they use disambiguating acoustic information to correctly identify the target word (e.g., *sandal*) and rule out similar-sounding competitor words (e.g., *sandwich*; Marslen-Wilson, 1990). Access of the predicted word and suppression of competition from similar-sounding words become more efficient across development (e.g., Fernald et al., 1998; Rigler et al., 2015; Sekerina & Brooks, 2007).

Children and adults with CIs recognize spoken words less efficiently than individuals with NH (Farris-Trimble et al., 2014; Grieco-Calub et al., 2009; McMurray et al., 2017). Postlingually deafened adults with CIs show a delay in successful prediction of target words (Farris-Tremble et al., 2014). While listeners with NH quickly use early-arriving phonemes (e.g., *dr*) to predict upcoming sounds (e.g., *ink*), postlingually deafened individuals with CIs appear to wait to get more information before committing to recognition of the target word (Farris-Tremble et al., 2014). Prelingually deafened children with CIs also show a delay in spoken word recognition; 2-year-old children with CIs are less accurate and take longer to access the meaning of the word they hear in comparison to their age-matched peers with NH (Grieco-Calub et al., 2009). Even older prelingually deafened individuals with CIs (ages 12–25 years) show less efficient spoken word recognition; they show less competition from cohort competitors (e.g., *sandwich,* when hearing *sandal*) and more competition from rhyme competitors (e.g., *candle,* when hearing *sandal*; McMurray et al., 2017). These differences in the dynamics of spoken word recognition suggest that listeners with CIs wait to access the target word and cohort competitors rather than immediately accessing based on early-arriving phonological information and then subsequently wait to rule out rhyme competitors until the acoustic signal is further processed.

Inefficient processing at the word level may have cascading consequences for language comprehension, as each perceived word must be both recognized and integrated into an overall sentence structure and meaning. However, there are other processes, such as top-down prediction, that may be playing a role in sentence comprehension for children with CIs.

Sentence-Level Prediction

The limited research investigating use of top-down prediction by children with CIs has suggested that they may not consistently use sentence context to predict upcoming speech input (Conway et al., 2014; Eisenberg et al., 2002). Conway et al. (2014) asked children to listen to and repeat back sentences containing three key words (e.g., That *kind* of *airplane* is *brown*); they looked for evidence of children using earlier words to predict later words. Children with NH listening to spectrally degraded speech showed improvement across the sentence, suggesting that they were using sentence context to improve word recognition. The children with CIs did not show such improvement across the sentence, suggesting that they did not use sentence context to aid in word recognition. However, there were large overall differences in accuracy across groups, with the children with NH showing much lower accuracy scores than the children with CIs. Perhaps the latter group's greater experience with degraded speech resulted in higher accuracy of the first word, leaving less opportunity to detect improvements in accuracy of the subsequent words.

Eisenberg et al. (2002) also sought to investigate children with CI's use of sentence context with a sentence repetition task, finding that, while a subset of children with CIs demonstrated benefit from perceiving words in the context of sentences, other children with CIs did not, appearing to process the sentences as "strings of unrelated words" (p. 459). While Conway et al. (2014) and Eisenberg et al. (2002) address the question of whether children with CIs are able to use sentential context to aid word recognition, the sentence repetition task relies on both the productive and receptive language systems to carry out the experimental task. If the question is specifically about how children use language knowledge to facilitate language comprehension, then the most sensitive task would primarily rely on the receptive system. Otherwise, it is possible that features of an individual child's speech motor system are also influencing task performance. An eye-tracking study that is sensitive to differences in real-time processing as the sentence unfolds would more directly tap into the ability of children with CIs to use sentential context to facilitate recognition of upcoming words and how this predictive ability may relate to individual differences in language knowledge (i.e., vocabulary size).

Additionally, the sentence stimuli used in previous studies rely on listeners using syntactic context to predict words in the sentence, as the sentences are designed to have minimal semantic cues (Conway et al., 2014; Eisenberg et al., 2002). For example, in the sentence, "That *kind* of *airplane* is *brown,*" the available words may aid in predicting the syntactic classes of upcoming words but do not appear to be semantically predictive. More recent studies utilizing word processing tasks have found that both adults and children with CIs demonstrate better performance when sentences include informative semantic context (Holt et al., 2016; Patro & Mendel, 2018). These findings suggest that the presence of semantic cues early on in a sentence may aid listeners with CIs in more quickly and accurately identifying upcoming words in a sentence.

Semantic Prediction

Children with NH use lexical-semantic cues to predict upcoming words in a sentence (e.g., Borovsky et al., 2012; Mani & Huettig, 2012; Nation et al., 2003). Children as young as 2 years old are capable of using semantic information in the verb (e.g., *eat*) to predict thematically appropriate arguments (e.g., *cake*), as measured by looks toward images of thematically appropriate arguments while listening to sentences in an eye-tracking experiment (Borovsky et al., 2012; Mani & Huettig, 2012).

Semantic prediction is a process in which one's knowledge about perceived words can facilitate processing of upcoming words. Recognition of upcoming words can be facilitated by increasing both activation of the predicted word and suppression of phonologically related words, such as cohort competitors. When adults with NH perceive a semantically informative verb, they no longer consider phonological competitors of the subsequent target noun (Dahan & Tanenhaus, 2004). When the target word is not preceded by a semantically constraining verb, adult listeners consider the cohort and target words up until the moment of disambiguation in the target word. In this way, the dynamics of lexical competition can be influenced by the presence of prior lexical-semantic cues.

Dahan and Tanenhaus (2004) and Brock et al. (2008) provide evidence that semantic prediction can facilitate recognition of upcoming words by suppressing competition from similar-sounding words. Children with CIs experience difficulties with speech recognition due to their device's limitations in transmission of spectral information. Semantic prediction may present a way in which a CI user's top-down language knowledge can aid recognition of upcoming words.

The available evidence on sentence processing in children with CIs suggests that these children may sometimes use context to aid processing, but there may be differences relative to their peers with NH. In lexical processing, there is evidence that children with CIs utilize a wait-and-see strategy, perhaps in order to reduce the risk of incorrect commitments and the need for subsequent revision (McMurray et al., 2017). A similar wait-and-see strategy might be enacted at the sentence level: Even when children with CIs have adequate semantic knowledge to utilize a lexical-semantic cue, they could choose to delay semantic prediction until there is increased certainty in the upcoming argument. If so, phonological competitors would also be considered during perception of the target word in order to allow for potentially inaccurate prediction.

Another possibility is that children with CIs utilize semantic cues for prediction when they are available, but delayed vocabulary development makes prediction more difficult. For example, if a child is less familiar with the word containing the lexical-semantic cues or has a less well-developed semantic network, this may hinder the child's ability to use the cues to accurately and efficiently predict upcoming words. Children with CIs are more likely to have below average vocabulary size, and these delays in vocabulary development could underlie difficulties with processing language efficiently in real time. Vocabulary size is related to efficiency in spoken word recognition by children with CIs, with children with larger vocabularies displaying more efficient word recognition (Grieco-Calub et al., 2009). It is possible that individual differences in vocabulary size among children with CIs predict efficiency and accuracy of sentence-level processing, along with word-level processing.

Alternatively, children with CIs may rely more on semantic context than their peers with NH, as top-down processes based on language knowledge may be more reliable than the bottom-up acoustic information from the speech signal. Both lexical access and lexical competition have been shown to be less efficient in spoken word recognition by prelingually deafened individuals with CIs (Grieco-Calub et al., 2009; McMurray et al., 2017). However, listeners with CIs could use semantically informative words to more quickly access upcoming words and subsequently suppress potential competing words. This ability would be particularly helpful for listeners with CIs, as their word-level processing difficulties lie in inefficient suppression of similar-sounding competitors (McMurray et al., 2017). In addition, the degraded signal may result in the presence of a larger cohort of similar-sounding lexical competitors, which would take more time to suppress if they were considered during perception of the target word. For these reasons, semantic prediction may be a useful compensatory tool during language processing for individuals with CIs.

This Study

In this study, we investigated whether 5- to 10-year-old children with CIs use lexical-semantic information to facilitate access of upcoming words and how this ability compares to both age-matched and vocabulary-matched peers with NH. Children in this range of elementary school ages would be expected to show some use of semantic prediction (Borovsky et al., 2012; Mani & Huettig, 2012; Nation et al., 2003). In addition, individual differences in use of semantic prediction in childhood have been linked to individual differences in language ability (Borovsky et al., 2012; Mani & Huettig, 2012; Nation et al., 2003). This age range also encompasses a period of language development in which children transition from learning to read to reading to learn, which is expected to yield a wide range of language abilities and allow for insights into the effects of age and individual differences in language ability on language processing.

Similar to studies by Dahan and Tanenhaus (2004) and Brock et al. (2008), semantic prediction was operationalized by both facilitated access of the target word and increased suppression of phonological competitors in the presence of a lexical-semantic cue. The first question in this study was whether children with CIs demonstrate the use of semantically informative cues to facilitate spoken word recognition. If children with CIs show earlier looks to the arget and decreased looks to the cohort following a semantically informative cue, this would demonstrate their ability to use semantic prediction to aid spoken word recognition. We also examined whether individual differences in hearing experience and vocabulary ability predict children's ability to use semantic cues to facilitate spoken word recognition.

We then investigated how the language processing performance of children with CIs compares to children with NH, including comparisons to a group of children matched for age and another group matched for vocabulary ability. Comparison of the performance of children with CIs to both age-matched and vocabulary-matched children with NH allowed for the investigation of whether semantic prediction during sentence processing is more directly related to age, vocabulary knowledge, or hearing status.

Method

Participants

Twenty-four children aged 5–10 years of age (M_{age} = 8;1 [years;months], range: 5;0–10;11, 13 girls) with CIs who were learning spoken English as their primary mode of communication were recruited from local clinics. All were implanted within the established sensitive period for development of the central auditory system (i.e., by 4 years; *M* = 19 months, *SD* = 11 months, range: 9–8 months) and were experienced CI users with at least 3 years of CI use (*M* = 80 months, *SD* = 20 months, range: 39–119 months). Twenty-one children had bilateral CIs, two were bimodal (CI with hearing aid in contralateral ear), and one had a unilateral CI (with bilateral hearing loss).

Forty-two children with NH also participated in this study. From that pool of children, we selected 24 age-matched and 24 vocabulary-matched children to act as comparison groups for the children with CIs (six children were included as both age and vocabulary matches for different children with CIs). Age matches were intended to be matched within 3 months of age, and 22 children with CIs were appropriately matched to children with NH. However, due to research restrictions put in place in response to public health concerns regarding COVID-19, the final two age matches could not be recruited. Instead, the two remaining children with CIs were matched to children with NH within 7 months of age in a manner that maintained the group comparability by both mean and range of ages (one younger and one older). In this way, all 24 children with CIs were matched by age to 24 children with NH (M_{age} = 8;1, range: 5;5–10;10, 12 girls).

Children were individually matched by vocabulary ability using the Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4; Dunn & Dunn, 2007). The use of a standardized vocabulary test offers a limited estimation of vocabulary ability for each child rather than a more specific measure of vocabulary such as vocabulary size, but this procedure has been frequently used to construct vocabulary-matched groups in language development research (e.g., Sheng & McGregor, 2010). Raw scores were converted into age-equivalent scores in order to match children with vocabulary differences spanning 6 months of age or less. Nineteen matches were constructed using this criterion. Again, the final five matches could not be recruited due to research restrictions in response to the COVID-19 pandemic. The remaining five children with CIs were matched to children with NH by having age-equivalent scores within 10 months of age, maintaining group comparability. With these additional matches, all 24 children with CIs were matched by receptive vocabulary ability to 24 children with NH (mean chronological age = 7;0, range: 5;0–10;8, 12 girls). Ages, test scores, and statistical comparisons across groups are shown in Table 1.

Materials

Each trial in the eye-tracking experiment included four images and one auditory target sentence. The creation and design of visual and auditory materials are described below.

Auditory Stimuli

Each sentence contained a person subject (e.g., *The brother*), either a semantically informative or semantically neutral monosyllabic verb (e.g., *draws* or *gets*), a determiner and a neutral monosyllabic adjective (*the small*), followed by a final noun (monosyllabic or disyllabic) that is more likely to follow the semantically informative verb (e.g., *picture,* predicted by *draws* but acceptable with *gets*). The neutral adjective was included in order to lengthen the time window between the onset of the verb and the onset of the final noun and allow additional time for predictive processing as well as the initiation of eye movements to the pictures on the screen as a result of language processing (see Mani & Huettig, 2012, for a similar stimuli design). The adjectives were the same across the verb conditions of each sentence item. Sentences were designed to avoid phonological overlap between the target noun and previous words (e.g., *sees the old horn* instead of *hides the old horn*). Semantically informative verbs were judged to sufficiently predict the target noun from results of a cloze task administered via an online survey for adults in Amazon Mechanical Turk (for detailed information about the norming of sentence stimuli, see Supplemental Material S1).

All key words in the sentences (subject, verb, adjective, and final noun) and the cohort competitors had an age of acquisition (AoA) less than 6 years (Kuperman et al., 2012). There was no significant difference in AoA or lexical frequency across the target and competitor nouns (p > .05).

Table 1. Means and standard deviations of age-matched and vocabulary-matched comparison groups for age, Peabody Picture Vocabulary Test–Fourth Edition (PPVT-4), Expressive Vocabulary Test–Second Edition (EVT-2), and Kaufman Brief Intelligence Test–Second Edition (KBIT-2).

	Age matched					Vocabulary matched			
Variable	CI *M* (*SD*) Range	NH *M* (*SD*) Range	*t*	*df*	Sig.	NH *M* (*SD*) Range	*t*	*df*	Sig.
Age (months)	98 (19) 66–131	98 (18) 65–130	−.02	46.00		84 (26) 60–128	2.10	41.52	**
PPVT-4 AES (months)	95 (37) 44–176	135 (47) 51–275	−3.22	43.83	**	95 (35) 49–173	.08	45.77	
PPVT-4 SS	96 (20) 61–143	122 (14) 87–160	−5.26	40.57	***	107 (11) 86–126	−2.40	35.10	*
EVT-2 SS	96 (11) 75–120	111 (12) 86–141	−4.41	44.17	***	107 (12) 86–129	−3.22	45.91	**
KBIT-2 SS	101 (18) 73–129	114 (16) 74–137	−2.67	44.99	*	103 (19) 66–129	−.26	43.98	

Note. CI = cochlear implant group; NH = normal-hearing group; AES = age equivalent score; SS = standard score.
*$p < .05$. **$p < .01$. ***$p < .001$.

There was also no significant difference in the AoA of informative and neutral verbs ($p > .05$). Unsurprisingly, neutral verbs, which are more general, were found to be more frequent than informative verbs, which are more specific, $t(30) = −3.34$, $p < .01$.

Sentence stimuli were recorded by a female native speaker of mainstream American English using a Shure SM51 microphone in a sound-attenuated room. One hundred milliseconds of silence were added to the beginning of each stimulus, and they were normalized to the same intensity. The mean sentence length was 2,414 ms (*SD* = 140), with the verb onset time-locked to the average verb onset (694 ms) and the onset of the predicted final noun time-locked to the average final noun onset (1,714 ms). Time locking was carried out by slightly slowing or speeding up the speech before and within the time-locked window in Praat (Boersma & Weenink, 2018).

In addition to the 18 sentence pairs, there were an additional 18 filler trials in which the neutral verb sentence was followed by the cohort competitor (e.g., *gets the small pickle*) as the target rather than the original target word (*picture*). These trials were included in order to ensure that the cohort competitors would be considered as possible targets in all trials. Filler trials were not included in statistical analyses of the eye gaze data.

Each participant completed two blocks of the experiment. Each block contained the 36 experimental sentences and nine filler trials. The sentences appearing in each block were presented in a semirandomized order, with the restriction that the two members of each neutral-informative pair could not be presented consecutively.

Cohort competitors were selected to create maximum overlap with the onset of the target word, while also maintaining an appropriate AoA and frequency level for this age range. For this reason, some pairs demonstrate more overlap than others (e.g., *horn/horse* vs. *kite/couch*). For a full list of the sentence stimuli and paired distractor objects, see Supplemental Material S1.

Visual Stimuli

Each sentence stimulus was presented with four images, one representing the target object (e.g., *picture*), another representing the cohort competitor (e.g., *pickle*), and the two others being a target and cohort for a different sentence stimulus that were phonologically and semantically unrelated to the other pair (e.g., *cookies* and *costume*). In this way, the picture stimuli from two sentence pairs were presented on the screen at once, ensuring that all objects had the same number of syllables and were semantically appropriate with the same neutral adjective. In addition, all four objects on the screen were constructed to be equally plausible with the neutral verb and easily represented by a color photograph. Each word had two picture referents, with one being presented in the first block of the experiment and the other presented in the second block. There were 72 total images. The images were edited so as to maintain a consistent level of coloring and brightness within each set of images. The edited images were then normed on 3- to 5-year-old children in four preschool classrooms at the University of Maryland Center for Young Children (for detailed information about the norming of visual stimuli, see Supplemental Material S1). In the Visual World Paradigm task, each set of four images (target, cohort, unrelated target, and unrelated cohort) appeared on the screen at once, with each image randomly assigned to one of the four quadrants of the computer screen.

Other assessments. Prior to testing, children with NH passed an abbreviated hearing screening with a portable audiometer, demonstrating a behavioral response to tones at 1000, 2000, and 4000 Hz at 25 dB in both ears. Children with CIs passed a Ling Six Sound Test (Ling, 2002), in which the experimenter produced isolated sounds (/ʃ, m, a, s, u, i) from behind a speech hoop in a randomized order. The child was asked to repeat each sound back to the experimenter. Participants also completed two standardized vocabulary assessments. The PPVT-4 was used to estimate receptive vocabulary ability. Expressive vocabulary ability was assessed using the Expressive Vocabulary Test–Second Edition (EVT-2; Williams, 2007). In addition, participants completed the Matrices subtest of the Kaufman Brief Intelligence Test–Second Edition (KBIT-2; Kaufman & Kaufman, 2004) as an abbreviated measure of nonverbal cognitive ability.

The test scores and statistical comparisons for these measures between the participant groups are presented in Table 1. The age-matched group of children with NH had significantly higher test scores than the children with CIs for the PPVT-4, EVT-2, and KBIT-2 Matrices.

The children with CIs did not significantly differ from the vocabulary-matched group with NH for their age-equivalent and raw scores on the PPVT-4 and EVT-2; their KBIT-2 standard scores were also similar. These vocabulary-matched children with NH were younger than the children with CIs and, as a result, had significantly higher standard scores for PPVT-4 and EVT-2. Raw scores for both PPVT-4 and EVT-2 were converted to growth score values (GSV) in order to add them into the statistical models of eye gaze. GSV are a Rasch linear transformation of raw scores and thus are better fit for inclusion in regression analyses.

Procedure

Eye movements were recorded with either an SR Research arm-mounted EyeLink 1000 Plus or an EyeLink Portable Duo eye tracker. Test sessions took place at the University of Maryland, in offices at Johns Hopkins Listening Center, or in private meeting rooms at public libraries. At the beginning of each trial, participants saw four pictures in the center of the four quadrants of the computer monitor for 1,200 ms. After that, an attention-getting video (e.g., a looming bulls-eye) appeared in the center. Once the participant looked to this cue for 800 ms, the attention-getter disappeared, the cursor appeared in the center of the screen, and the trial began. An auditory stimulus then played through speakers, and the participant clicked on the image matching the last word of the sentence stimulus by touching the image on the touch screen monitor with a touch screen stylus pointer. The trial ended when the participant clicked on one of the images after the sentence ended. The EVT-2 was administered after the first block of the Visual World Paradigm task, and the PPVT-4 and KBIT-2 Matrices subtest were administered after the second block.

Data Cleaning

Point of eye gaze was sampled at every 2 ms starting at the onset of each trial (after the central fixation point) and continued until the participant clicked on a picture. Data processing was carried out in RStudio (Version 1.0.153) using the eyetrackingR package (Version 1.8; Dink & Ferguson, 2015). Areas of interest (AOIs) were defined as 450 × 450 pixel squares in which the picture referents were presented with the boundaries of objects extended by 30 pixels to account for noise in the eye track. This did not result in overlap between objects. The target AOI refers to the quadrant that holds the target, the cohort AOI holds the cohort distractor, and the unrelated AOIs refer to the two quadrants showing unrelated distractors. Missing data due to blinking were interpolated within a 150-ms time window, given that the position of the eyes before and after the missing data points were looking to the same AOI. It can be assumed that a saccade to a location other than that AOI could not occur within such a short time window.

Only trials in which the participant response with the pointer was correct were included in the statistical models for eye gaze. This cleaning resulted in 1% (46/4,752) of trials being dropped; this did not differ by group ($p > .05$). Track loss was defined as any sample where eye gaze was not recorded to be looking at the screen. Trials with more than 50% of track loss within the time window of analysis (see Statistical Analyses) were dropped. This cleaning resulted in 3.5% (165/4,706) of trials being dropped from target fixations analysis and 6.1% (289/4,706) from the cohort fixations analysis: This did not differ by group ($ps > .05$). The average track loss per participant in remaining trials was a little less than 5%, and this remaining track loss did not differ by group ($ps > .05$). In addition, blocks with less than 50% of trials in each condition were also removed. This cleaning resulted in zero blocks being removed from analyses.

Results

Response Accuracy

Accuracy was above 90% for each child, block, and condition. A logistic mixed-effects model (with accuracy as 0 or 1) was run for each comparison (age-matched and vocabulary-matched) to determine whether accuracy was significantly influenced by group membership (CI and NH) or experimental condition (neutral and informative). Models included a random intercept for participant (Barr et al., 2013). In both comparisons, neither group nor condition (nor their interaction) significantly predicted response accuracy ($ps > .05$).

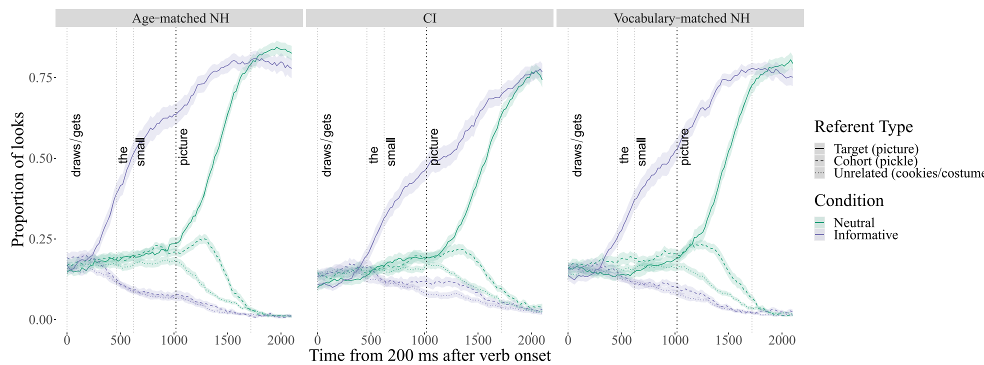
Eye Gaze

Figure 1 shows eye gaze patterns to the target, cohort competitor, and unrelated distractors for the children with CIs and both comparison groups with NH. All groups began looking to the target earlier and looked less to the cohort competitor in the informative condition relative to the neutral.

Statistical Analyses

Target fixations were analyzed within a 2-s time interval extending from 200 ms after verb onset to 1,100 ms after target word onset. This "prediction" time window starts at the verb onset in order to capture changes in target fixations in response to perception of an informative verb relative to a neutral verb. Cohort competition was analyzed in a shorter (1-s) "competition" time window, starting at 200 ms after the onset of the target word and ending at the same time point as the prediction time window. The competition

Figure 1. Time windows of analyses with eye gaze data. Proportion of looks to target, cohort, and unrelated referents for each condition (neutral and informative) across groups (age-matched normal hearing [NH], cochlear implant [CI], and vocabulary-matched NH). Time 0 ms indicates 200 ms after verb onset. Dotted lines indicate the average onset of each word in the sentence stimuli with a 200-ms delay. The length of the *x*-axis represents the prediction time window for analysis of target fixations. The darker dashed line indicates the start of the competition time window for analysis for cohort fixations.



time window captures changes in cohort fixations in response to perception of the target word in the informative and neutral conditions. The time windows of analyses are displayed with the eye gaze data in Figure 1.

A general linear mixed-effects model was used to quantify differences in target and cohort fixations across conditions and groups, as well as individual differences related to vocabulary scores. For analysis of target fixations within the prediction time window, the number of fixations to the target AOI was divided by the number of total fixations to the screen in this time window to create a proportion measure.[1] A proportion measure for cohort fixations was calculated in the same manner within the competition time window.

For both models of target and cohort fixations, the dependent variable was regressed on the effect of condition (coded as 0 for *neutral* and 1 for *informative*), the effect of group (coded as 0 for *CI* and 1 for *NH*), and the interaction of Condition × Group. All models included a random intercept for participant.[2]

To investigate whether receptive or expressive vocabulary explained more variance in semantic prediction, PPVT-4 GSV and EVT-2 GSV were added to create a model of target fixations in the age-matched data set with receptive vocabulary and another with expressive vocabulary. Vocabulary scores were mean-centered and scaled before analysis to facilitate interpretation. Akaike information criterion values were compared to determine which vocabulary measure contributed to the best model fit. The model with PPVT-4 GSV scores yielded a lower (therefore better) Akaike information criterion value (−168.27) relative to the model with EVT-2 GSV scores (−156.37). PPVT-4 GSV was used as the vocabulary measure for all subsequent models. Although previous research has demonstrated a relationship between sentence processing and nonverbal abilities (Conway et al., 2014), the addition of KBIT-2 Matrices standard score to the statistical model of target fixations for this comparison did not significantly improve model fit, $\chi^2(4) = 2.62$, $p = .62$.

In addition to our models of eye gaze comparing semantic prediction across groups, we implemented a model of looks to target for the children with CIs to investigate the potential for age of first cochlear implantation, chronological age, and norm-referenced vocabulary ability to explain individual differences in language processing ability in this group of children. This model was similar to the other general linear mixed-effects models of target fixations in that it included condition as a predictor and the same random effect structure. This model also included three mean-centered and scaled predictors: age of implantation, chronological age, and PPVT-4 standard scores. PPVT-4 standard scores were included in this model rather than GSV scores due to the inclusion of age as a variable, which is highly correlated with PPVT GSV scores since they are derived from raw scores.

All analyses were performed in RStudio (Version 1.0.153) using the lme4 R package (Version 1.21; Bates et al., 2015). Models were fit using maximum likelihood estimation. The R code and fixed effects for all models are available in Supplemental Material S1.

[1]This proportion measure can also be computed with the denominator as total recorded fixations to AOIs, omitting fixations to the center of the screen in this calculation. We decided to include all fixations recorded on the screen since these non-AOI fixations appear mostly at the beginning of the time window and may reflect taking longer to make a decision following verb onset.

[2]Since a random intercept for item could not be included in this model given the aggregated data set, an item analysis was carried out to determine if inclusion of log frequency of the target word explained any of the observed condition or group effects or Condition × Group interactions. All effects of condition and group found in the participant analysis were also found in the item analysis, with the exception of the Condition × Group interaction in the vocabulary-matched comparison of target fixations ($p > .05$). For this reason, this interaction in the vocabulary-matched comparison should be interpreted with caution as we may not have the statistical power to generalize this result to spoken language beyond our experimental stimuli. The details of the item-level models and their results are available in the Supplemental Material S1.

Individual Differences in Children With CIs

In our analysis of individual differences in the group of children with CIs, we found a significant effect of condition ($\beta = .14$, $SE = .02$), $t(20) = 8.56$, $p < .001$, meaning children looked more to the target following an informative versus neutral verb. There was also an effect of PPVT standard score ($\beta = .04$, $SE = .02$), $t(27) = 2.11$, $p < .05$. Children with higher vocabulary for their age looked more to the target in general, demonstrating more efficient lexical processing. There were no significant effects of or interactions with age of implantation or chronological age (*p*s > .05).

Age-Matched Comparison

Target Fixations

For target fixations in the age-matched comparison, there was a significant main effect of condition ($\beta = .14$, $SE = .01$), $t(44) = 9.70$, $p < .001$. Children in both groups looked more to the target in the informative condition relative to the neutral. There was also a significant effect of group ($\beta = .07$, $SE = .03$), $t(60) = 2.70$, $p < .01$, indicating that the children in the group with NH were more accurate at looking to the target in the neutral condition in comparison to the group with CIs.

The interaction between Condition × Group was significant ($\beta = .05$, $SE = .02$), $t(44) = 2.36$, $p < .05$. The group with NH showed more of a difference in target fixations between conditions relative to the group with CIs, meaning children with NH demonstrated more facilitation of looks to the target in the informative relative to the neutral condition. Children with CIs showed this effect of condition on target looks but to a lesser extent. There was also a significant interaction between Condition × PPVT-4 GSV ($\beta = .03$, $SE = .01$), $t(44) = 2.20$, $p < .05$, indicating that children with CIs with higher vocabulary scores demonstrated more of an effect of condition on target fixations relative to children with CIs with lower vocabulary scores.

There was a significant three-way interaction between Condition × Group × PPVT-4 GSV ($\beta = -.05$, $SE = .02$), $t(44) = -2.33$, $p < .05$. This three-way interaction is illustrated in Figure 2A, which shows target fixations by condition with a median split in PPVT-4 GSV for the CI and age-matched group with NH. In the group with CIs, having a higher PPVT-4 GSV score predicted more difference in target looks across conditions. This result shows that children with CIs with higher vocabulary scores also showed more use of the semantic cue to facilitate lexical access in the informative condition. This interaction between vocabulary and semantic prediction ability did not appear in the age-matched group with NH, perhaps because even those with lower vocabulary scores in this group showed efficient use of the informative cue.

Cohort Fixations

The analysis of cohort fixations was carried out using the proportion measure computed from the competition time window, starting at 200 ms after onset of the target word.[3] There was a significant main effect of condition ($\beta = -.07$, $SE = .01$), $t(44) = -8.82$, $p < .001$. Children in both groups looked less to the cohort competitor in the informative condition relative to the neutral. There was also a significant Condition × PPVT-4 GSV interaction ($\beta = -.02$, $SE = .01$), $t(44) = -2.47$, $p < .05$, indicating that the effect of condition in the group with CIs was larger for children with higher vocabulary scores. For the group with CIs, children with higher vocabulary scores better suppressed the cohort competition in the informative relative to the neutral condition. This interaction is illustrated in Figure 2B, which shows cohort competition by condition with a median split in PPVT-4 GSV for the group with CIs and age-matched group with NH.

Vocabulary-Matched Comparison

The analysis of target and cohort fixations for the vocabulary-matched data set was carried out with the same models used in the age-matched comparison.

Target Fixations

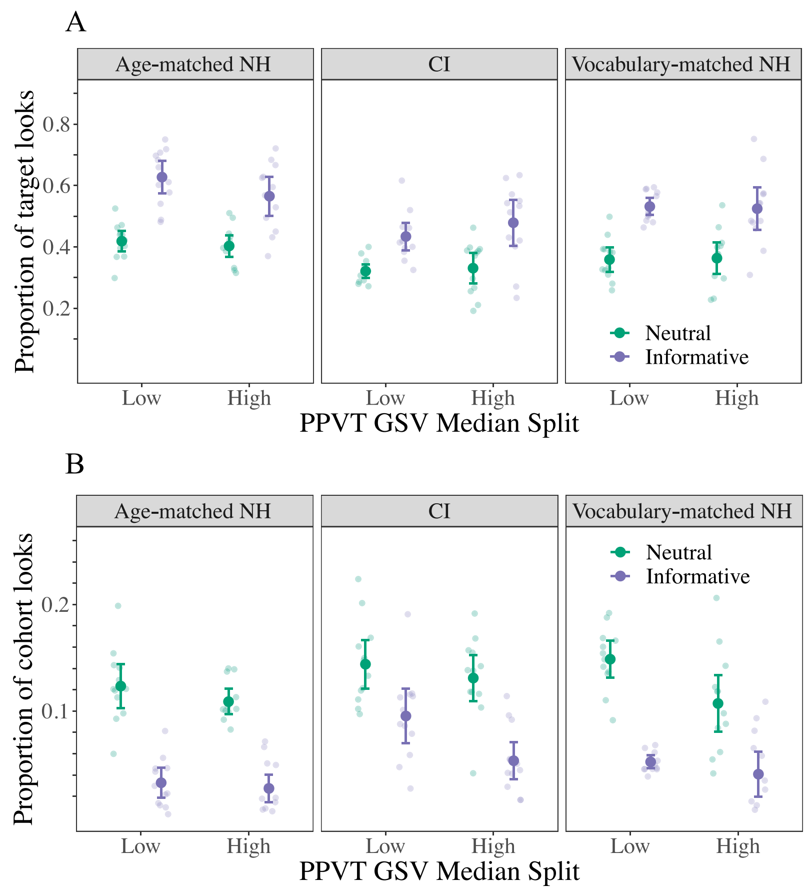
As in the age-matched comparison, there was a significant main effect of condition ($\beta = .13$, $SE = .01$), $t(44) = 10.83$, $p < .001$. Children in both groups looked more to the target in the informative condition relative to the neutral.

There was a significant Condition × Group interaction ($\beta = .04$, $SE = .02$), $t(44) = 2.09$, $p < .05$, where the group with NH showed more of a beneficial effect of condition on target fixations in comparison to the group with CIs. There was also a significant Condition × PPVT-4 GSV interaction ($\beta = .03$, $SE = .01$), $t(44) = 2.45$, $p < .05$, meaning children with CIs with higher vocabulary scores demonstrated more of a difference in target fixations across conditions relative to children with lower vocabulary scores.

There was a significant three-way interaction between Condition × Group × PPVT-4 GSV ($\beta = -.04$, $SE = .02$),

[3]Traditionally, analyses of eye gaze data choose a denominator (choosing either all fixations to the screen or only fixations to AOIs) for proportion calculations to quantify the data, and they keep this calculation constant throughout all of their analyses. As this is common practice, we have followed that practice here. However, it is possible that different analyses should choose different denominators for proportion calculations. For example, in this study, we have different time windows of analysis for target and cohort fixations. The target fixation analysis has an earlier time window, when children might not yet have enough information to make a definitive decision, so we opted to use all fixations to the screen (including ones to the center). However, by the beginning of the competition time window, listeners are able to immediately make decisions to look to AOIs, matching the onset of the target word to potential referents on the screen. Therefore, it might be more appropriate for the denominator for this analysis of cohort looks to be only fixations to one of the four AOIs, while keeping all fixations as the denominator for the analysis of target looks. In fact, when cohort fixations are quantified by a proportion calculation including only AOI looks, there is a significant effect of group ($\beta = -0.03$, $SE = .01$), $t(79) = -2.19$, $p < .05$, meaning children with CIs looked more to cohort competitors than their age-matched peers with NH.

Figure 2. Target accuracy and cohort competition for all groups across conditions with vocabulary median split. Proportion of looking to target in prediction time window (A) or cohort (B) within the competition time window by condition (neutral and informative) for each age group (age-matched normal hearing [NH], cochlear implant [CI], and vocabulary-matched NH). Each group is separated into a Peabody Picture Vocabulary Test (PPVT) growth score value (GSV) median split (low and high scores). Individual raw data are represented as lighter dots, while group averages and standard errors appear in darker colors.



$t(44) = -2.50$, $p < .05$. Figure 2A shows target fixations by condition with a median split in PPVT-4 GSV for the CI and vocabulary-matched group with NH. In the group with CIs, having a higher PPVT-4 GSV score predicted more difference in target looks across condition. As was also found in the age-matched comparison model, children with CIs with better vocabulary ability displayed more use of the informative cue to facilitate spoken word recognition. The interaction between vocabulary and semantic prediction ability does not appear to be present in the vocabulary-matched group with NH, maybe even trending in the opposite direction.

Cohort Fixations

As in the age-matched model, there was a significant effect of condition ($\beta = -.06$, $SE = .01$), $t(44) = -8.00$, $p < .001$. Children in both groups better suppressed cohort competition in the informative condition relative to the neutral. There was also a significant Condition × PPVT-4 GSV interaction ($\beta = -.02$, $SE = .01$), $t(44) = -2.28$, $p < .05$, showing children with CIs with higher vocabulary scores demonstrated more of an effect of condition on cohort fixations than children with lower vocabulary scores. There was a significant Group × PPVT-4 GSV interaction, as well ($\beta = -.03$, $SE = .01$), $t(76) = -2.74$, $p < .01$. In the group with NH, children with higher vocabulary scores demonstrated fewer looks to cohort in the neutral condition relative to children with lower vocabulary scores, while this effect of vocabulary was not present in the neutral condition for the group with CIs.

There was a significant three-way interaction between Condition × Group × PPVT-4 GSV ($\beta = -.04$, $SE = .01$), $t(44) = 3.78$, $p < .001$. In the group with CIs, children with higher vocabulary scores showed less looking to the cohort in the informative condition relative to children with lower vocabulary scores. In contrast, the interaction was in the opposite direction for the group with NH, with vocabulary scores affecting cohort fixations in the neutral condition rather than the informative condition. As a result, children with higher vocabulary scores in the group with NH showed less of a difference in cohort looks across conditions in comparison to children with lower vocabulary scores. This three-way interaction is illustrated in Figure 2B, which displays cohort fixations by condition with a median split in PPVT-4 GSV for the CI and vocabulary-matched group with NH.

Summary

Our analyses of eye gaze found that children with CIs used semantically informative cues to facilitate recognition of upcoming words via more efficient lexical access and better suppression of cohort competition. In comparison to both the age-matched group and the vocabulary-matched group with NH, the group with CIs showed less use of the informative cue to more efficiently look to the upcoming target word. In addition, there was a relationship between vocabulary and semantic prediction ability for the children with CIs, but not for either group of children with NH. Children with CIs with higher vocabulary scores demonstrated more use of the informative cue to facilitate lexical access. There was also a relationship between vocabulary and use of semantic prediction to suppress cohort competition for the group with CIs. Children with CIs with better vocabulary ability showed more efficient use of the informative cue to suppress cohort competition. This relationship between vocabulary and use of the informative cue to suppress cohort competition was not demonstrated by either group with NH.

Discussion

School-age children with CIs used sentence context, specifically lexical-semantic cues from familiar words, to predict upcoming words in a sentence. This prediction is characterized by both faster access of the target word and increased suppression of phonological competitors to the predicted word. This result contradicts findings from previous studies investigating use of sentence context by children with CIs (Conway et al., 2014; Eisenberg et al., 2002). Previous studies utilized sentence repetition as a method of investigating use of sentence context, which may not have been able to capture the real-time differences in sentence processing that online methods, such as eye tracking, provide. In addition, previous work focused on informative context operationalized as syntactic cues rather than lexical-semantic cues. It is possible that children with CIs immediately utilize some context cues (i.e., lexical-semantic) and not others (e.g., syntactic).

We found that age of implantation and chronological age did not have significant effects on lexical processing or semantic prediction ability in children with CIs. For children with CIs in this age range, duration of deafness and experience with CI input do not appear to influence their lexical processing efficiency or ability to use semantic cues to facilitate spoken word recognition. However, norm-referenced vocabulary ability does explain some of the variability in lexical processing efficiency in this group. Borovsky et al. (2012) likewise found that semantic prediction ability was related to norm-referenced vocabulary rather than age.

While children with CIs demonstrated semantic prediction, they benefitted less from semantic cues relative to their peers with NH. Matching children for vocabulary and the inclusion of vocabulary scores in the statistical models helped to account for fundamental group differences in vocabulary ability, as the differences observed in the vocabulary-matched comparison were smaller than those in the age-matched comparison. Previous studies of spoken word recognition in children with CIs have not used vocabulary matching to equate vocabulary ability between children with CIs and their peers with NH (Grieco-Calub et al., 2009; McMurray et al., 2017). Inclusion of a vocabulary-matched group of children with NH allowed us to compare language processing between children with CIs and their peers with NH while accounting for potential delays in vocabulary development for the children with CIs (Lund, 2019). Vocabulary clearly plays a role in semantic prediction ability, as the children with CIs demonstrated semantic prediction that was more similar to their vocabulary-matched peers with NH than their age-matched peers with larger vocabularies. However, significant differences in semantic prediction ability still remained between children with CIs and children with NH with similar vocabulary ability. In contrast, group differences in spoken word recognition (e.g., lexical access in the neutral condition) observed in the age-matched comparison appear to be explained by group differences in vocabulary ability, as children with CIs performed similarly to children with NH who are matched for vocabulary ability.

The question remains of what mechanism (or mechanisms) lies behind these group differences in semantic prediction. One possibility is that less efficient sentence-level processing by children with CIs relative to their peers with NH may be linked to differences in hearing status. Children with CIs have qualitatively different hearing experiences from their peers with NH, including listening to a spectrally degraded signal in each instance of spoken language comprehension, as well as learning language from this degraded speech signal. Observed inefficiencies in language processing by children with CIs have been demonstrated in listeners with NH when presented with spectrally degraded speech (McMurray et al., 2017; Newman & Chatterjee, 2013). While these findings were at the lexical level, they suggest that observed delays or inefficiencies in language processing by listeners with CIs may be partially explained by the degraded speech signal simply being more difficult to parse in the moment.

Another potential explanation for less efficient semantic prediction in children with CIs is that acquiring language knowledge via a degraded signal may result in less well-developed structure in the language system. For example, children with CIs demonstrate a lower level of categorical precision than their peers with NH (Bouton et al., 2012). While some phonemic categories appear to develop age-appropriately, such as voicing contrasts (Caldwell & Nittrouer, 2013), others present more difficulty for listeners with CIs.

Specifically, phonemic contrasts that rely on spectral features (i.e., place of articulation, nasality) are less reliably identified and discriminated by children with CIs, demonstrating that poor transmission of spectral cues by CIs has developmental implications (Bouton et al., 2012). In addition, children with CIs show deficits in phonological awareness, especially at the phonemic level (Lyxell et al., 2008; Nittrouer et al., 2012). In contrast to phonemic awareness, syllabic awareness is less reliant on spectral cues and more dependent on perception of the temporal amplitude envelope. Since temporal information is typically transmitted well by CIs, it could be predicted that children with CIs would show a relative strength in or typical development of awareness of syllabic structure, and this has been observed in some studies (James et al., 2009). Collectively, these findings suggest that children with CIs demonstrate qualitative differences in the phonological structure of the lexicon that can be linked to the spectrally degraded nature of the speech signal they perceive via their CIs. When children with CIs are perceiving spoken words, each word must be accessed via navigation of a less well-structured lexicon. For example, words with more difficult sounds may have more neighbors, or neighbors may be less distinguishable from one another. Although we did not find group differences in word-level processing across children with CIs and children with NH matched for vocabulary ability, inefficiency in accessing lexical information could still be having cascading effects on the sentence-level processing ability to use semantic cues to facilitate processing of upcoming words.

Along with impacting phonological lexicon structure, learning language via a degraded signal may also result in less well-developed semantic network structure compared to that of age-matched peers with NH (Kenett et al., 2013). Kenett et al. (2013) utilized verbal fluency data from 7- to-10-year-old children with CIs and age-matched peers with NH to construct semantic networks and compare organization across groups, finding that the semantic networks for children with CIs were underdeveloped compared to their peers with NH. This suggests that even if a word were accessed with the same efficiency, the ability to use the semantic information within the word to activate other semantically associated words would be hindered by a less-developed semantic network structure within the lexicon.

There are also other ways in which the structure and content of language knowledge of children with CIs may differ from children with NH, as children with CIs tend to perform more poorly than their peers with NH in multiple domains of speech and language (Nittrouer & Caldwell-Tarr, 2016). While matching by a measure of vocabulary helps to account for baseline differences in vocabulary ability, there may be differences in other language domains (e.g., receptive grammar, vocabulary depth) that are not captured by a single vocabulary measure. It is possible that group differences in other domains of language could help to explain the inefficiencies in semantic prediction ability of children with CIs in comparison to their peers with NH.

Children with CIs demonstrated a positive relationship between vocabulary and semantic prediction ability, characterized by facilitated lexical access and suppressed phonological competition in the presence of an informative cue. Neither group of children with NH displayed this same relationship. This raises the question of why vocabulary and semantic prediction ability were not related for children with NH in this study when previous studies have demonstrated this relationship (Borovsky et al., 2012; Mani & Huettig, 2012). One explanation is that the age-matched children with NH had larger vocabularies overall, and the relatively low AoA criteria for the words included in the experiment may have been easier to process for this group of children with NH. While this hypothesis would match our findings for the age-matched comparison, it is somewhat contradicted by our findings for the vocabulary-matched comparison since this younger group of children with NH also did not demonstrate the relationship between vocabulary and semantic prediction ability observed in the group of children with CIs. The lack of relationship between vocabulary and semantic prediction ability for both groups of children with NH suggest that language processing may rely on vocabulary knowledge to the extent that the task taxes the language system. Even though children with CIs demonstrated more similar performance to children with NH with similar vocabulary ability, perceiving a degraded signal may make the task more challenging in ways that are not measured in our eye-tracking task but could be detected with other online processing measures (e.g., pupillometry). If this were the case, then speech perception ability could be a third variable explaining the relationship between vocabulary and semantic prediction ability. Perhaps children with better speech perception had less difficulty with the listening task and thus were better able to utilize their vocabulary knowledge. It is also possible that children with better speech perception have also been better able to learn more words and thus show better semantic prediction.

Limitations

A limitation of this study is that it did not include an independent measure of speech perception ability for the group of children with CIs. Individual differences in speech perception ability would help to explain variation in vocabulary and semantic prediction. Future studies on spoken language processing by children with CIs would benefit from inclusion of a measure of speech perception, such as the Spectrotemporal Ripple for Investigating Processor Effectiveness (Archer-Boyd et al., 2018).

The small sample size of this study also presents limitations in our ability to detect some of the investigated effects. In this study, group differences appeared in lexical access, but not in cohort competition. Children with CIs demonstrated less efficient in lexical access without demonstrating significant differences in resolution of phonological competition relative to their peers with NH. Given previous findings of differences in resolution of cohort competition during spoken word recognition (McMurray et al., 2017), the most likely explanation for the lack of group differences observed in cohort competition in the neutral condition in this study is a lack of statistical power. This study used a statistical model of eye gaze that did not include time course, so it was less sensitive to the dynamics of lexical competition across time in comparison to models of eye gaze that include time course (see McMurray et al., 2017). In addition, while the model for lexical access involved larger proportions and a more expansive time window of analysis, the lexical competition model utilized much smaller proportions and a smaller time window. It is possible any group effect was too small in magnitude to detect with this type of statistical analysis and this size of participant pool. Especially given the increased variability in language performance of children with CIs, larger sample sizes in future studies of language processing in this population would aid in detection of group differences and allow for more analyses of individual differences to help to explain the variation in outcomes within this population.

Implications and Future Directions

The finding that children with CIs are able to use semantic cues to facilitate efficient word recognition has both theoretical and clinical implications. This finding raises the question of how these children may use other contextual cues to aid language processing. There is evidence to suggest that listeners with CIs utilize both semantic and prosodic cues to aid in language comprehension (Holt et al., 2016; Huang et al., 2017; Patro & Mendel, 2018) and may benefit from syntactic sentential context in a sentence repetition task (Eisenberg et al., 2002). Continued research into how children with CIs can use sentence context during language processing will allow us to better understand the strategies these children use to aid comprehension of a degraded speech signal. Further research should investigate whether this predictive mechanism is amenable to some type of clinically relevant, clinically feasible training. Since some predictive processes have been shown to be amenable to experience in listeners with NH (Qi et al., 2011; Ryskin et al., 2017), they may be effective targets of experience-based intervention for children with CIs who struggle with language comprehension.

It is important to consider whether the use of semantic prediction in children with CIs is a maladaptive or adaptive strategy in sentence listening. For children who do not use this prediction at all, training on this predictive skill may provide a compensatory strategy for difficult listening situations. However, for children who use semantic prediction and show less efficient use of this skill, it is possible that this decreased efficiency is an adaptive process designed to reduce the cost of potential revision if their prediction turns out to be inaccurate. For this reason, we should be cautious in how we proceed in the clinical application of this finding. Perhaps there is a "happy medium" in this situation, where clinical training helps children to predict more without pushing them to revise more often.

Though the current study showed evidence of children predicting upcoming words, the specific mechanism behind this result should be inferred with caution. As discussed by Huettig and Mani (2016), there is little empirical evidence that prediction per se is necessary for understanding language. For example, implicit, passive processes such as spread of activation across a semantic network may lead to similar facilitation for lexical access, as does outright prediction. This would fall in line with our finding that vocabulary was related to the extent of semantic facilitation by children with CIs. Children with larger vocabularies are more likely to have stronger semantic associations between words and more expansive semantic networks. Under this account, clinical interventions such as vocabulary instruction and other methods with the purpose of expanding and deepening vocabulary knowledge may be able to facilitate efficient sentence processing via strengthening of semantic connections between words.

Conclusions

The primary goal of this study was to determine whether children with CIs use semantic prediction to benefit sentence comprehension and whether their semantic prediction ability is comparable to their peers with NH. Children with CIs demonstrated reliable use of semantically informative cues to facilitate access of upcoming words and suppress lexical competition. However, children with CIs demonstrated less efficient semantic prediction relative to children with NH, even when matched for vocabulary ability. Receptive vocabulary played an important role in semantic prediction for the children with CIs, as children with larger vocabularies showed more efficient use of semantic cues to benefit access of upcoming words. These findings have implications for research as they point to future directions of inquiry, including whether there are other top-down processes (e.g., syntactic, prosodic) at play in sentence processing by children with CIs. In addition, future research is needed to specify the mechanisms underpinning this semantic prediction ability in children with CIs, as they have yet to be clearly identified. There are clinical implications as well, given that some top-down processes in sentence comprehension have been shown to be amenable to training (Qi et al., 2011; Ryskin et al., 2017). Semantic prediction could serve as a potential avenue for clinical intervention with children with CIs in order to support more efficient language comprehension.

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