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Research Article

# Deaf Children With Cochlear Implants Do Not Appear to Use Sentence Context to Help Recognize Spoken Words

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**Purpose:** The authors investigated the ability of deaf children with cochlear implants (CIs) to use sentence context to facilitate the perception of spoken words.
**Method:** Deaf children with CIs ($n = 24$) and an age-matched group of children with normal hearing ($n = 31$) were presented with lexically controlled sentences and were asked to repeat each sentence in its entirety. Performance was analyzed at each of 3 word positions of each sentence (first, second, and third key word).
**Results:** Whereas the children with normal hearing showed robust effects of contextual facilitation—improved speech perception for the final words in a sentence—the deaf children with CIs on average showed no such facilitation. Regression analyses indicated that for the deaf children with CIs, Forward Digit Span scores significantly predicted accuracy scores for all 3 positions, whereas performance on the Stroop Color and Word Test, Children's Version (Golden, Freshwater, & Golden, 2003) predicted how much contextual facilitation was observed at the final word.
**Conclusions:** The pattern of results suggests that some deaf children with CIs do not use sentence context to improve spoken word recognition. The inability to use sentence context may be due to possible interactions between language experience and cognitive factors that affect the ability to successfully integrate temporal–sequential information in spoken language.

For most users of spoken language, a sentence is perceived as a string of related words. The relatedness that exists between words is adaptive, especially under noisy or degraded listening conditions, in which knowledge of the semantic and syntactic structure of language can help the listener perceive what is being said (Hale, 2006; Miller & Selfridge, 1950; Obleser, Meyer, & Friederici, 2011; Rubenstein, 1973). The brain appears to take whatever information is useful and available at the moment, including the words that were just spoken, to help implicitly predict, anticipate, and perceive upcoming words and to successfully decode the meaning of an utterance (Elman, 1990; Kalikow, Stevens, & Elliott, 1977; Van Berkum, 2008).

It is well established that most users of language benefit considerably from such use of sentence context; that is, listeners use information provided from previously spoken words in an utterance to help perceive, recognize, and understand subsequent words (Elliott, 1995; Miller, Heise, & Lichten, 1951). The information provided by the previously spoken words in a sentence includes both semantic and syntactic context that helps constrain the possible ways a sentence might end. Overwhelming evidence has shown that both younger and older adults use sentence context to compensate for decreased levels of hearing or audibility of speech (Dubno, Ahlstrom, & Horwitz, 2000; Sommers & Danielson, 1999; Wingfield, Lindfield, & Goodglass, 2000). For instance, Grant and Seitz (2000) tested postlingually deafened young adults with varying levels of residual hearing on their ability to perceive words presented in semantically meaningful sentences or in isolation. The participants with hearing impairment showed better performance when the words were presented in a meaningful context. Furthermore, they showed greater use of sentence context for less intelligible words. Thus, sentence context appears to help listeners recognize words in sentences under difficult or degraded listening conditions.

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Although the role of sentence context has been under investigation for some time, a surprising lack of research has examined the use of sentence context in the speech perception of children who are deaf and hard-of-hearing. In one of the few studies to have done so, Stelmachowicz, Hoover, Lewis, Kortekaas, and Pittman (2000) assessed speech perception for high- (semantically correct) and low- (semantically anomalous) predictability sentences in children with hearing impairment (ages 5–12), children with normal hearing (NH; ages 5–10), and adults with NH. The intensity of speech stimuli was varied for all participants to create a range of stimuli at different audibility levels. The results of the study showed that children with NH and adults with NH displayed improvements in word recognition within the mid-range of audibility when the words occurred in high-predictability compared to low-predictability sentences; that is, the participants with NH showed performance gains when semantic context was available. However, the children with hearing impairment did not show comparable gains when sentence context was available. Furthermore, vocabulary scores (as measured by the Peabody Picture Vocabulary Test—III [PPVT–III]; Dunn & Dunn, 1997) were weakly correlated with the use of sentence context in both the children with NH and those with hearing impairment. These findings indicate that the ability to use sentence context to compensate for poor speech intelligibility may be compromised in children who are hard of hearing and may possibly be due to lack of experience with spoken language. However, given the weak nature of the correlation between vocabulary and use of sentence context, it may be that lack of experience with spoken language is not the only factor contributing to the relatively lower sentence context gains in children with hearing impairment.

However, Stelmachowicz et al. (2000) examined children with hearing impairment who had bilateral sensorineural hearing loss in the mild to moderately severe range, not profoundly deaf children with cochlear implants (CIs). To assess the word and sentence perception abilities of children with CIs, Eisenberg, Martinez, Holowecky, and Pogorelsky (2002) used a set of lexically controlled sentences, which accounted for both the frequency of each word in natural language and the words' phonemic similarity to other words in natural language (Kirk, Pisoni, & Osberger, 1995). The sentences contained target words that were considered lexically easy or lexically hard, based on the word frequency and the frequency of the phonemes in the word. Lexically easy words are words that are frequently heard by children but are phonetically different from most other words in a child's vocabulary. The assumption is that children with CIs would be more likely to know a word that they have heard often, and that sounds unlike the other words they typically hear, thus allowing them to maximize their previous experience and rely less on auditory information in the speech signal. Lexically hard words, on the other hand, are words that are not frequently heard and are similar to many other words in a child's vocabulary. Thus, the children have less experience with these words, and the words themselves are more difficult to acoustically distinguish from other words (see Kirk et al., 1995).

The results from Eisenberg et al.'s (2002) study showed that children had systematically higher recognition performance with sentences made up of lexically easy words compared to lexically hard words. In addition, for the deaf children with CIs and the children with NH listening to spectrally degraded stimuli, most children showed an effect of sentence context, which was operationalized as better speech perception performance for words in sentences compared to isolated words. However, the three lowest performing deaf children with CIs showed a striking lack of sentence context use, with words in sentences being recognized less accurately than words in isolation. Eisenberg et al. concluded that these children were encoding the sentences "as strings of unrelated words." They also suggested that these children might be relying heavily on verbal short-term memory to encode, store, and recall each word in a sentence, rather than relying on previous words in a sentence to help with recognition. However, as the authors acknowledged, they did not have empirical evidence to support these suggestions because that was not the original goal of the study.

One characteristic of Eisenberg et al.'s (2002) study is that their findings on the use of sentence context were derived by comparing sentence recognition performance for words in sentences compared to isolated words. An alternative approach is to compare word recognition performance at different points in a sentence, with the use of sentence context operationalized as having better word recognition scores for words at the ends of sentences compared to words at the beginnings. This pattern would provide an "online" measure of performance because it occurs at different points in a sentence, possibly providing more insight into sentence-processing operations as they unfold over time.

Another important unanswered question deals with the underlying factors that contribute to successful use of sentence context in deaf children with CIs. If meaningful variation among sentence context use exists within this population, it is important to understand what demographic and cognitive factors might help understand the nature of such variation. Chronological age and age at implantation have both been shown to influence spoken word recognition, speech perception performance, and other language outcomes (see, e.g., Nicholas & Geers, 2007; Tomblin, Barker, & Hubbs, 2007; see also Stelmachowicz et al., 2000, for effects of chronological age on speech perception in children with NH and those with hearing impairment), but the extent to which these factors also contribute to the ability to use sentence context to improve spoken word recognition is not clear. In terms of cognitive factors, several studies have established that verbal short-term memory is a reliable predictor of spoken language outcomes in deaf children with CIs (Dawson, Busby, McKay, & Clark, 2002; Pisoni & Cleary, 2003); however, it is likely that verbal short-term memory capacity is not as important for using sentence context. Instead, recent work suggests that cognitive control processes

—the ability to select a particular interpretation from among competing possibilities—may be more critical to the use of sentence context, at least in listeners with NH (January, Trueswell, & Thompson-Schill, 2009; Novick, Trueswell, & Thompson-Schill, 2005; Obleser, Wise, Dresner, & Scott, 2007). The reason is that understanding a sentence requires integrating multiple cues from a variety of sources (including the sentence and referential context in which a word occurs), leading to multiple alternative possible representations being partially activated. According to this view, cognitive control is necessary to inhibit competing representations (e.g., words less likely to occur given the current sentence context) and bias attention and processing resources toward the most likely interpretation (the word that is most likely to occur). Thus, in listeners with NH the use of sentence context appears to rely to a large extent on cognitive control abilities.

If cognitive control is in fact important for using sentence context, then deaf children with CIs might be at a disadvantage. Recent findings suggest that deaf children with CIs have difficulties with domain-general cognitive control processes (Beer, Kronenberger, & Pisoni, 2011; Beer, Pisoni, & Kronenberger, 2009; Houston et al., 2012; Pisoni, Conway, Kronenberger, Henning, & Anaya, 2010). It is therefore possible that delays with domain-general cognitive control abilities—that is, cognitive control abilities that cut across different cognitive functions and processes rather than being specific to language—negatively affect the ability of deaf children with CIs to successfully use sentence context to help understand spoken language, over and above any difficulties they may have due to lack of experience hearing and using spoken language itself.

The two goals of the current study were (a) to investigate the extent to which deaf children with CIs are able to use sentence context to help facilitate spoken word recognition and (b) to understand what demographic, language, and other cognitive factors might explain variation in the children's use of sentence context. To accomplish the first goal, we examined spoken word recognition performance for deaf children with CIs at different points in a sentence. The use of sentence context was expected to result in better word recognition scores at the end of a sentence compared to the beginning as the amount of semantic and syntactic information increases. For this study, we operationalized the use of sentence context simply as how much gain in word recognition performance is observed for words toward the end of a sentence relative to words toward the beginning of a sentence. On the basis of the previous literature investigating sentence perception (Eisenberg et al., 2002; Stelmachowicz et al., 2000) and cognitive control processes in this population (Beer et al., 2011), we expected that deaf children with CIs on average would show a lower use of sentence context compared to an age-matched group of children with NH. To accomplish the second goal, we also obtained several cognitive and linguistic measures (short-term memory, cognitive control, and vocabulary) from the deaf children with CIs to determine possible associations with the use of sentence context. If Eisenberg et al.'s (2002) hypothesis is correct and some deaf children with CIs rely heavily on verbal short-term memory abilities to recognize words in sentences, then we would expect short-term memory capacity to be correlated with individual word recognition scores. In contrast, given the previous research on adults with NH (January et al., 2009), we predicted that cognitive control processes (as measured by the Stroop Color and Word Test, Children's Version; Golden, Freshwater, & Golden, 2003) would be associated with greater ability to use sentence context to recognize spoken words.

## Experiment 1: Deaf Children With CIs

### *Method*

Children were tested by a trained speech-language pathologist at the DeVault Otologic Research Laboratory, Department of Otolaryngology, Indiana University School of Medicine, Indianapolis. The research study received approval from the local institutional review board at the Indiana University School of Medicine.

#### Participants

Twenty-four prelingually and profoundly deaf children with CIs (age range: 5–10 years, 15 males) were recruited through the DeVault Otologic Research Laboratory at the Indiana School of Medicine. All the children had profound bilateral hearing loss (90 dB or greater), had received a CI by age 4, and had used their implant for a minimum of 3 years. All participants were native speakers of English and had hearing parents. Although several of the children had been exposed to Signed Exact English, none relied exclusively on sign or gesture, and all children were tested using oral-only procedures. All children had a single CI except for two children with bilateral implants and one child who had a hearing aid in the nonimplanted ear. For the three children with bilateral hearing, testing was conducted with only one CI activated (the original implant). Aside from hearing loss, there were no other known neurocognitive, motor, or sensory impairments. Etiology of deafness included unknown (*n* = 17), genetic (*n* = 3), ototoxicity (*n* = 1), and mondini dysplasia (*n* = 2). The demographic characteristics of these 24 children are summarized in Table 1. For their time and effort, the children's parents/caregivers received monetary compensation.

**Table 1.** Participant characteristics of deaf children with cochlear implants (CIs) (*n* = 24).

| Measure | *M* | *SD* | Range |
|---|---|---|---|
| Age[a] | 90.0 | 19.4 | 61–118 |
| Age at implant[a] | 21.0 | 8.2 | 10–39 |
| CI duration[a,b] | 69.1 | 19.0 | 36–98 |

[a]In months. [b]Duration of CI use.

### Sentence Materials

We used a set of English lexically controlled sentences developed by Eisenberg et al. (2002). The sentences were originally developed on the basis of the theoretical principles of the *neighborhood activation model* (Luce, 1986; Luce & Pisoni, 1998), which takes into account the lexical properties of spoken words that may make them more or less easily recognizable. These word properties include *word frequency*, or the likelihood of a word occurring in the participants' native language; *neighborhood frequency*, or the number of words that are phonetically similar to the target word; and *neighborhood density*, or the degree of phonetic similarity between words in a lexical neighborhood (see Kirk et al., 1995). We included both lexically easy and lexically hard sentences because it was possible that sentence context would be used differently according to sentence difficulty. For example, context might be more helpful in recognizing "hard" words in sentences because perhaps words in the "easy" sentences would be distinct enough to perceive easily regardless of the amount of context available.

The words from Eisenberg et al.'s (2002) study that made up each sentence were taken from Logan (1992), who pulled them from the Child Language Data Exchange System database (MacWhinney & Snow, 1985). The Child Language Data Exchange System database comprises 994 words from the spoken language of typically hearing 3- to 5-year-old children. Because these words were taken from 3- to 5-year-olds' expressive vocabularies they are expected to be understood by children whose receptive vocabularies fall at least within this range.

The sentences consisted of 20 lexically easy (i.e., high word frequency, low neighborhood density) and 20 lexically hard (i.e., low word frequency, high neighborhood density) sentences. Each sentence contained three key words at three positions in the sentence (first, second, and third). Audio recordings of the sentences were obtained from Laurie Eisenberg and are the same as speech files used in Eisenberg et al.'s (2002) study. As reported by Eisenberg et al., there were only occasional discrepancies in the intensity levels across words in the sentences (ranging from +5.6 dB to −9.3 dB), with intensity not fluctuating systematically across the three word positions. A full list of the sentences is provided in the Appendix.

### Sentence Perception Task Procedure

All the children were tested individually in a quiet environment. The 40 sentences described above were presented free field in the clear through a high-quality loudspeaker (Advent AV570) at 65 dB SPL. The children were instructed to listen closely to each sentence and then repeat back what they heard to the experimenter, even if they were able to perceive only one word of the sentence. All children were also encouraged to guess even if they were not confident in their responses; this was done in order to maximize the number of words reported by each child, with the assumption that many of a child's "guesses" might be accurate due to having partially formed or partly unconscious representations of the words. All deaf children with CIs were tested by the same experimenter, who was extremely diligent in her efforts to encourage children to report as many words as possible and not to focus exclusively on any individual word.

First, two practice sentences were presented. Children received feedback after they made their responses to the practice sentences. Next, all 40 of the test sentences (20 "easy" and 20 "hard") were presented in random order to the children, with no feedback given. The children's responses were recorded onto digital audiotape and were later scored offline based on the number of key words (0–3) correctly repeated for each sentence. Scoring was done on an all-or-none basis. Only words that were presented in the correct serial order and exactly matched the target word were scored as correct responses.

### Neuropsychological Measures

In addition to the sentence perception task, all children also completed three standardized neuropsychological tests to measure (a) verbal short-term memory, (b) receptive vocabulary, and (c) cognitive control abilities. These measures were then used in a series of regression analyses to explore possible associations with sentence perception scores and the use of sentence context. Scores from these three measures are reported in Table 2.

*Verbal short-term memory*. The Forward and Backward Digit Span tasks of the Wechsler Intelligence Scale for Children—Third Edition (Wechsler, 1991) was used to measure verbal memory capacity. In the Forward Digit Span task, participants were presented with sequences of prerecorded spoken digits with lengths (two to 10) that became progressively longer. The participants' task was to

**Table 2.** Performance of the deaf children with CIs on neuropsychological measures.

| Measure | *M* | *SD* | Range |
|---|---|---|---|
| Digit Span | | | |
| Forward | 4.9 | 1.6 | 2–8 |
| Backward | 2.5 | 1.5 | 0–5 |
| PPVT–III | | | |
| Raw score | 96.2 | 24.7 | 61–158 |
| Scaled score | 85.5 | 12.1 | 59–107 |
| Stroop Word | | | |
| Raw score | 46.6 | 18.4 | 9–80 |
| T score | 56.7 | 11.2 | 42–85 |
| Stroop Color | | | |
| Raw score | 34.6 | 9.6 | 18–55 |
| T score | 48.9 | 6.5 | 34–59 |
| Stroop Color–Word | | | |
| Raw score | 19.8 | 7.5 | 5–40 |
| T score | 43.1 | 10.0 | 26–66 |

*Note.* Forward and Backward Digit Span scores are number correct out of 18 total; Peabody Picture Vocabulary Test—III (PPVT–III) scaled scores are normed such that a score of 100 represents the mean; Stroop T scores are normed such that a score of 50 represents the mean.

repeat each sequence aloud. In the Backward Digit Span task, participants were also presented with sequences of spoken digits with lengths that became progressively longer, but they were asked to repeat the sequence in reverse order. Digits were played through the loudspeaker at 65 dB; the child's responses were recorded by a desk-mounted microphone and scored for accuracy offline. Participants received one point for each test item that they correctly recalled in each digit span task. Two test sequences were presented at each sequence length. When a child incorrectly recalled both digit sequences at a given length, testing ended.

In general, the Forward Digit Span task is thought to reflect the involvement of passive processes that maintain and store verbal items in short-term memory for a brief period of time, whereas the Backward Digit Span task reflects the operation of controlled attention and higher level executive processes that allow for the manipulation and processing of verbal items held in immediate memory (Rosen & Engle, 1997).

*Receptive vocabulary*. The PPVT–III is a standard measure of vocabulary development for individuals ages 2 years and up. In this task, participants are shown four pictures on a single trial. They are prompted by the examiner with a spoken English word and then asked to pick the picture that most accurately depicts the word. For each child, a scaled score is derived on the basis of a comparison with a large normative sample, where a score of 100 represents the mean and 15 represents ±1 *SD*.

*Stroop Color and Word Test*. The Stroop Color and Word Test, Children's Version, is based on the classic Stroop effect (Stroop, 1935) showing that attempting to name the color hue in which a word is printed is interfered by the linguistic content of the word itself. Being able to ignore the printed word and name the color hue is believed to require cognitive control, that is, the active suppression or inhibition of competing stimuli or representations (the printed word) and a reallocation of attention to other stimuli or representations (the color hue).

The Stroop test incorporates three conditions: (a) Word, (b) Color, and (c) Color–Word. Each condition is printed on a separate page that contains 100 items, and the child must read or identify as many of these items as possible within 45 s. The Word page contains 100 words (e.g., *RED*, *GREEN*, and *BLUE*) printed in black ink, and the task is to read the words. The Color page contains 100 items written as *XXXX*, printed in either red, green, or blue ink, and the task is to identify the color of each item. Finally, the Color–Word page contains a list of 100 words (e.g., *RED*, *GREEN*, and *BLUE*) printed in either red, green, or blue ink, with the color of the ink never matching the word itself. The task on the Color–Word page is to name the color of the ink, not the word itself. For all three conditions, the number of items correctly identified in the time limit was scored for each child (raw scores). A T score for each page can also be derived on the basis of a comparison with a large normative sample, where a score of 50 represents the mean and 10 represents ±1 *SD*.

## *Results*

### Overall Effects of Word Type and Word Position

The children's accuracy scores based on word type (easy or hard) and word position (first, second, or third target word in a sentence) are shown in Figure 1. A 2 × 3 repeated measures analysis of covariance (ANCOVA) was run on the accuracy scores, with item type (easy or hard) and word position (first, second, or third) as within-subject variables and age and raw PPVT–III score as covariates due to the large age range of participants and the potential effect of absolute level of vocabulary on ability to understand the sentences. The analysis revealed a significant effect of word position, $F(2, 42) = 11.41$, $p < .001$, $\eta_p^2 = .35$, with performance on the middle (second) word being lower than on the first and third words. There was no significant main effect of word type, $F(1, 21) = 2.14$, $p = .16$; easy words were not recognized better than hard words. There was also no interaction between word type and word position, $F(2, 42) = 0.91$, $p = .41$. However, these results must be interpreted with caution because of a significant interaction between position and one of the covariates: PPVT–III, $F(2, 42) = 4.22$, $p = .02$, $\eta_p^2 = .17$. There were no other significant interactions involving either of the covariates, chronological age, and raw PPVT–III score.

To further investigate the interaction between PPVT–III and word position, PPVT–III scores and scores for words at each position were plotted in a scatter plot and fitted with trend lines (see Figure 2). These plots showed very little difference in the relationship between PPVT–III and word score at each position. This, combined with the very small effect size ($\eta_p^2 = .17$) of the interaction between PPVT–III and position in the ANCOVA (much smaller than the effect size for the main effect of position, $\eta_p^2 = .35$), suggests that there is a significant main effect of word position despite the interaction with PPVT–III. To determine whether the effect held without PPVT–III as a covariate, a 2 × 3 repeated measures analysis of variance

**Figure 1.** Percentage accuracy of deaf children with CIs for easy (dotted line) and hard (solid line) sentences at each word position (1, 2, and 3). Error bars represent standard errors.

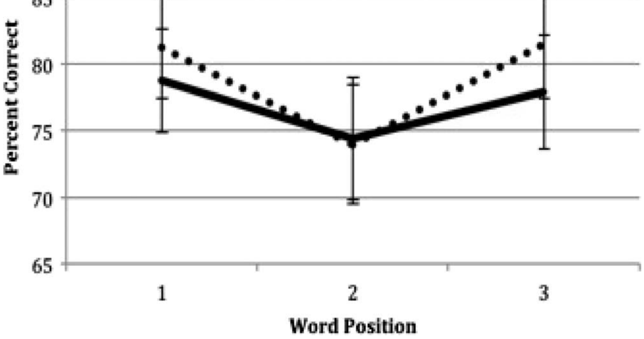
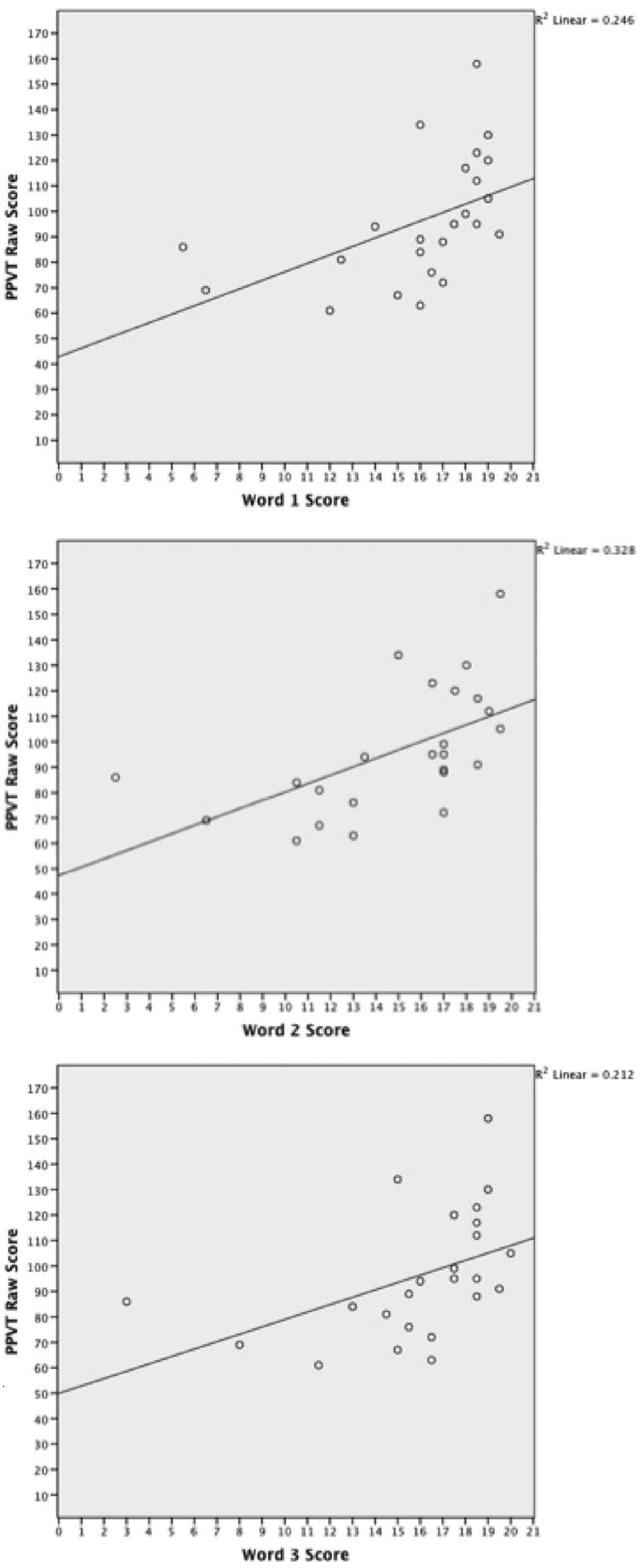


**Figure 2.** Scatter plot of total (averaging easy and hard words) Word 1 (Panel A), Word 2 (Panel B), and Word 3 (Panel C) scores against PPVT–III raw scores fitted with trend lines for deaf children with CIs.



was run on the accuracy scores, with item type (easy or hard) and word position (first, second, or third) as within-subject variables. As in the ANCOVA, the analysis revealed a significant effect of word position, $F(2, 46) = 10.26$, $p < .001$, $\eta_p^2 = .31$, with performance on the middle (second) word being lower than on the first and third words. There was no main effect of word type, $F(1, 23) = 2.04$, $p = .17$; easy words were not recognized better than hard words. There was also no interaction between word type and word position, $F(2, 46) = 1.00$, $p = .38$. Because no effects of word type were found, in all subsequent analyses reported in this article scores for easy and hard words were averaged together.

To explore the extent to which the children used sentence context to improve sentence perception for the third target word, we calculated a difference score for each child: $S_{3,1}$ was computed as performance on the third target word minus performance on the first target word for each sentence. One-sample *t* tests revealed that children on average showed no improvement between the first and third words ($S_{3,1} = -.063$), $t(23) = 0.81$, $p = .81$. This analysis revealed that, as a group, the children did not show any improvement across word positions that would be expected if they were using sentence context to improve word recognition. Instead, the children's scores reflected a *U*-shaped curve, reminiscent of the traditional serial position effect observed in studies of serial recall (Murdock, 1962; Postman & Philips, 1965).

### Associations With Demographic and Neuropsychological Measures

Although as a group there was no effect of sentence context, an examination of the range of values for $S_{3,1}$ revealed that nine children had scores that were numerically higher than 0, indicating that some children may have been gaining benefit from sentence context. In an attempt to understand the nature of such variation in the use of sentence context as well as in overall raw sentence performance accuracy at each word position, we next examined possible associations between performance on the sentence perception task and the other demographic and neuropsychological measures we obtained.

The raw and scaled scores for the children on the four neuropsychological measures (Forward and Backward Digit Span, PPVT–III, and Stroop) are presented in Table 2. Performance on the scaled PPVT–III scores was significantly lower than the population mean of 100, $t(23) = -5.89$, $p < .001$, roughly 1 *SD* lower than what would be expected for typically developing children of the same age.[1] On the

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[1] Note that although the deaf children with CIs had receptive vocabulary scores below the population average, the mean receptive language age on the PPVT–III for the group ($M$ = 7 years and 5 months, $SD$ = 2 years and 3 months) was well above the expressive age range for the words used to create test sentences (3–5 years). Thus, we expected that the children were able to understand the meaning of the words used in these sentences.

other hand, for the Stroop test, performance on the Word page was significantly higher than the population mean of 50, $t(23) = 2.92$, $p < .01$, indicating above-average ability of these children to read the three color words aloud.[2] This also suggests that reading of these particular words can be considered a relatively automatic process for this group of children and validates the use of the Stroop test itself. Performance on the Color page was not significantly different from the population mean, $t(23) = -0.84$, $p = .41$. Finally, however, performance on the Color–Word page was significantly lower than the population mean, $t(23) = -3.34$, $p < .005$. Note that performance on the Color–Word page can be considered an index of cognitive control, or the ability to inhibit the automatic reading response to the word in order to successfully name the color of the ink. On the basis of these three scores, this group of children appears to have slightly poorer cognitive control abilities overall compared to what would be expected for children with NH of the same age.

To determine whether cognitive control, vocabulary, or digit span abilities predict performance on the sentence perception task, three hierarchical linear multiple regression analyses were run, one for each of the three word positions (Word 1, Word 2, and Word 3). The independent variable added in the first step was chronological age, in the second step age at implantation was added, and in the third step all remaining independent variables (Forward Digit Span, Backward Digit Span, PPVT–III raw scores, and Stroop Color–Word raw scores) were added. Note that raw scores were used because this was expected to capture the most variability in the children's scores. The results of the regression analyses showed that in the final model, Forward Digit Span significantly predicted Word 1 performance ($\beta = .62$, $p = .018$; overall model fit: $R^2 = .323$) and marginally significantly predicted Word 3 performance ($\beta = .48$, $p = .074$; overall model fit: $R^2 = .254$). On the other hand, both Forward Digit Span ($\beta = .47$, $p = .042$) and PPVT–III raw scores ($\beta = .48$, $p = .040$) significantly predicted Word 2 performance (overall model fit: $R^2 = .450$). These results reveal a heavy reliance on verbal short-term memory for recognizing words presented in sentences, with Forward Digit Span performance predicting how well each child did on individual target words within each sentence. Full models for these three regression analyses are presented in Tables 3 through 5.

One last stepwise linear regression analysis[3] was run for the calculated difference score ($S_{3,1}$). Again, the independent variables were chronological age, age at implantation, Forward Digit Span, Backward Digit Span, PPVT–III raw scores, and Stroop Color–Word raw scores. The results of this analysis showed that Stroop Color–Word raw scores, rather than Forward Digit Span, significantly predicted gains made on Word 3 compared to Word 1 as calculated by $S_{3,1}$ ($\beta = .52$, $p < .01$; overall model fit: $R^2 = .238$). A scatter plot of $S_{3,1}$ and Stroop Color–Word raw scores is shown in Figure 3. Note that a higher raw Color–Word score means more items correctly identified in the 45-s time limit, thus indicating better cognitive control processes. The full model for this regression analysis is presented in Table 6.

In sum, the regression analyses of the raw sentence scores indicate that the children appeared to be relying on verbal short-term memory abilities (and, to a lesser extent, vocabulary knowledge) to help recognize the words in each sentence. In contrast, the difference score for Word 3 relative to Word 1 ($S_{3,1}$) was predicted not by verbal short-term memory or vocabulary knowledge but by the Color–Word page of the Stroop test, suggesting that better cognitive control abilities are associated with better use of sentence context, that is, better performance at the end of sentences relative to the initial parts of sentences. This last finding is consistent with recent research suggesting that cognitive control processes allow the language user to integrate sequential context in spoken language in order to select the correct interpretation from among competing possibilities (January et al., 2009). Although January et al.'s (2009) findings were specific to garden path recovery, it is likely that similar processes apply here.

## Experiment 2: Children With NH

In Experiment 1, the deaf children with CIs showed a lack of sentence context use. This was evident in the pattern of performance across the three word positions. If they were using sentence context, we would expect Word 3 performance to be greater than Word 2 performance and Word 2 performance to be greater than Word 1 performance. In addition, this pattern might be particularly evident for the lexically hard sentences. Instead, we observed equivalent performance on Words 1 and 3 and lower performance on Word 2, for both easy and hard sentences. Previous research has demonstrated that adults use context to facilitate word recognition (Dubno et al., 2000; Sommers

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[2] Although it seems unusual that deaf children with CIs would score above average on a test involving reading, the Stroop Word test is not designed to test reading per se; it measures only the speed of reading for the common words *red*, *blue*, and *green*. Thus, a high score on this test does not necessarily imply good reading skills overall but rather the ability to quickly read through a list composed of these three words only. Although there were two weak outliers in the data with particularly high Word T scores of 85, analysis of the data with these two points removed still resulted in a mean Stroop Word T score significantly above the population mean, $t(21) = 2.6$, $p = .016$.

[3] Hierarchical regression was not used for this analysis because none of the three models was found to be a good fit: Model 1 (chronological age), $F(1, 22) = 0.17$, $p = .683$, $R^2 = -.037$; Model 2 (chronological age, age at implantation), $F(2, 21) = 0.47$, $p = .634$, $R^2 = -.049$; Model 3 (chronological age, age at implantation, Forward Digit Span, Backward Digit Span, PPVT–III raw score, Stroop Color–Word raw score), $F(6, 17) = 1.72$, $p = .176$, $R^2 = .158$. However, the stepwise regression was a good fit, $F(1, 22) = 8.18$, $p < .01$, $R^2 = .238$.

**Table 3.** Summary of hierarchical regression analysis for variables predicting Word 1 for the deaf children with CIs.

| | Model 1 | | | | Model 2 | | | | Model 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | ***B*** | ***SE B*** | **β** | ***p*** | ***B*** | ***SE B*** | **β** | ***p*** | ***B*** | ***SE B*** | **β** | ***p*** |
| Chronological age | 0.06 | 0.04 | .32 | .13 | 0.06 | 0.04 | .30 | .17 | –0.02 | 0.05 | –.08 | .76 |
| Age at implantation | | | | | 0.02 | 0.10 | .04 | .85 | 0.10 | 0.08 | .21 | .27 |
| Forward Digit Span | | | | | | | | | 1.41 | 0.54 | .62 | .02 |
| Backward Digit Span | | | | | | | | | –0.32 | 0.65 | –.13 | .62 |
| PPVT–III | | | | | | | | | 0.05 | 0.04 | .31 | .21 |
| Stroop Color–Word | | | | | | | | | 0.08 | 0.09 | .17 | .38 |
| Adjusted $R^2$ | | .06 | | | | .02 | | | | .32 | | |
| $R^2$ change | | .10 | | | | .002 | | | | .40 | | |

& Danielson, 1999; Wingfield et al., 2000), but fewer studies have investigated sentence context use in children. Therefore, to determine whether the lack of sentence context observed in Experiment 1 is a consequence of deafness and cochlear implantation per se, rather an effect of age more generally, in Experiment 2 we collected data from an age-matched group of children with NH. The procedures were identical to those of Experiment 1 except that the sentence perception task incorporated spectrally degraded vocoded versions of the same sentences in an effort to simulate the acoustic transformations of a CI. If children with NH of the same age display a more robust use of sentence context, it would suggest profound differences in the ways that deaf children with CIs and children with NH process spoken sentences.

## Method

Children were tested in a sound-attenuated booth in the Speech Research Laboratory at Indiana University Bloomington. Before beginning the experiment, all children received and passed a brief pure-tone audiometric screening assessment in both ears. This study received approval from the local institutional review board at Indiana University.

*Participants.* Thirty-one (17 males) typically developing, age-matched children with NH (mean age in months: 88.8, range: 65–107) were recruited through Indiana University's Kid Information Database and through the Life Education and Resource Home Schooling Network of Bloomington. All children were native speakers of English; parental reports indicated no history of a hearing loss, speech impairment, or cognitive or motor disorder. For their participation, children received a small toy and their parents received monetary compensation.

*Sentence materials.* We used the same sentences as in Experiment 1 (see Appendix). Because we wanted to avoid performance at ceiling levels, these sentences were spectrally degraded to four spectral channels using a sine wave vocoder (www.tigerspeech.com), which is designed to simulate the listening conditions of a CI (Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). This is also the same procedure used by Eisenberg et al. (2002) to simulate CI processing and had earlier produced sentence scores between 35% and 60% for children with NH ages 5–12 years (Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000).

*Sentence perception task procedure.* The procedure was identical to that of Experiment 1, except that the sentences were presented to all participants under spectrally degraded conditions.

*Neuropsychological measures.* The same neuropsychological measures administered to the deaf children with CIs were administered to the children with NH as well. These included Forward Digit Span, Backward Digit Span, PPVT–III, and Stroop Color and Word Test.

## Results

*Overall effects of word type and word position.* The children's accuracy scores based on word type (easy or hard) and word position (first, second, or third target word in a sentence) are shown in Figure 4. As in Experiment 1, a 2 × 3 repeated measures ANCOVA was run on the accuracy

**Table 4.** Summary of hierarchical regression analysis for variables predicting Word 2 for the deaf children with CIs.

| | Model 1 | | | | Model 2 | | | | Model 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | ***B*** | ***SE B*** | **β** | ***p*** | ***B*** | ***SE B*** | **β** | ***p*** | ***B*** | ***SE B*** | **β** | ***p*** |
| Chronological age | 0.07 | 0.05 | .30 | .16 | 0.07 | 0.05 | .32 | .15 | –0.07 | 0.05 | –.30 | .24 |
| Age at implantation | | | | | –0.04 | 0.11 | –.08 | .71 | 0.04 | 0.09 | .08 | .65 |
| Forward Digit Span | | | | | | | | | 1.25 | 0.57 | .47 | .04 |
| Backward Digit Span | | | | | | | | | 0.46 | 0.68 | .16 | .51 |
| PPVT–III | | | | | | | | | 0.08 | 0.04 | .48 | .04 |
| Stroop Color–Word | | | | | | | | | 0.08 | 0.10 | .14 | .41 |
| Adjusted $R^2$ | | .05 | | | | .01 | | | | .45 | | |
| $R^2$ change | | .09 | | | | .01 | | | | .50 | | |

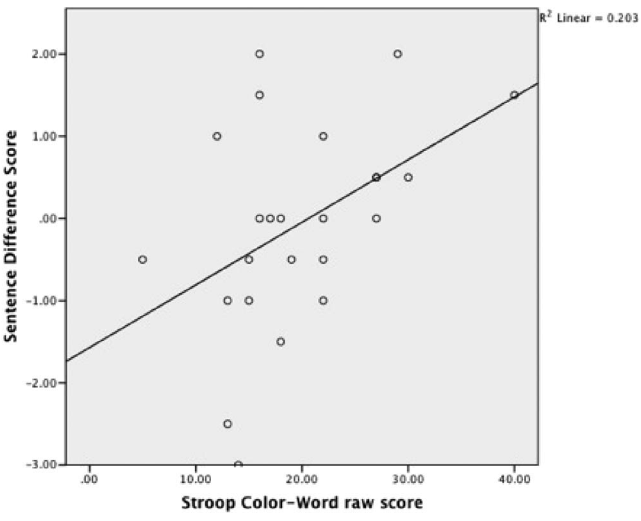
**Table 5.** Summary of hierarchical regression analysis for variables predicting Word 3 for the deaf children with CIs.

| | Model 1 | | | | Model 2 | | | | Model 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable** | ***B*** | ***SE B*** | **β** | ***p*** | ***B*** | ***SE B*** | **β** | ***p*** | ***B*** | ***SE B*** | **β** | ***p*** |
| Chronological age | 0.05 | 0.04 | .27 | .21 | 0.06 | 0.04 | .27 | .22 | –0.03 | 0.06 | –.17 | .55 |
| Age at implantation | | | | | –0.01 | 0.11 | –.03 | .91 | 0.06 | 0.09 | .12 | .54 |
| Forward Digit Span | | | | | | | | | 1.15 | 0.61 | .46 | .07 |
| Backward Digit Span | | | | | | | | | 0.14 | 0.72 | .05 | .85 |
| PPVT–III | | | | | | | | | 0.05 | 0.04 | .31 | .23 |
| Stroop Color–Word | | | | | | | | | 0.14 | 0.10 | .26 | .19 |
| Adjusted $R^2$ | | .03 | | | | –.02 | | | | .25 | | |
| $R^2$ change | | .07 | | | | .001 | | | | .38 | | |

scores, with item type (easy or hard) and word position (first, second, or third) as within-subject variables and chronological age and PPVT–III raw scores as covariates. The analysis showed a significant effect of word position, $F(2, 58) = 11.87$, $p < .001$, $\eta_p^2 = .29$, with performance on the last (third) word being higher than on the first and second words. There was a marginal effect of word type, $F(1, 29) = 3.86$, $p = .059$, $\eta_p^2 = .12$; easy words were recognized slightly better than hard words. Unlike in Experiment 1, there was also an interaction between word type and word position, $F(2, 58) = 3.57$, $p = .035$, $\eta_p^2 = .11$, with greater gains observed for the hard sentences. Because of the interaction with word type, in subsequent analyses reported below we did not average together the scores for easy and hard words but instead present results separately for each condition.

As in Experiment 1, to further explore the extent to which the children used sentence context to improve recognition of the third target word, we calculated a difference score for each child—$S_{3,1}$—for easy and hard sentences. One-sample $t$ tests revealed that whereas children with NH on average showed only a slight improvement between the first and third words for easy sentences ($S_{3,1} = 1.00$), $t(30) = 2.02$, $p = .052$, we observed a much larger improvement between the first and third words for the hard sentences ($S_{3,1} = 2.39$), $t(30) = 5.16$, $p < .001$. These analyses reveal that, as a group, the children with NH showed improvement across the word positions, especially for the hard sentence materials, that would be expected if they were using sentence context to improve word recognition. These results stand in sharp contrast to the results of the deaf children with CIs, which revealed a lack of such sentence context use.

**Figure 3.** Scatter plot of sentence difference scores ($S_{3,1}$) and Stroop Color–Word raw scores for deaf children with CIs.



*Associations with demographic and neuropsychological measures*. The raw and scaled scores for the children with NH on the four neuropsychological measures (Forward and Backward Digit Span, PPVT–III, and Stroop) are presented in Table 7. Performance on the scaled PPVT–III scores was significantly higher than the population mean of 100, $t(30) = 6.90$, $p < .001$, roughly 1 *SD* higher than what would be expected for typically developing children of the same age. For the Stroop test, performance on the Word page was also significantly higher than the population mean of 50, $t(30) = 7.70$, $p < .001$, indicating above-average ability of these children to read the three color words aloud. Performance on the Color page was not significantly different from the population mean, $t(30) = 1.50$, $p = .14$. Finally, however, performance on the Color–Word page was significantly lower than the population mean, $t(30) = −3.28$, $p < .005$.

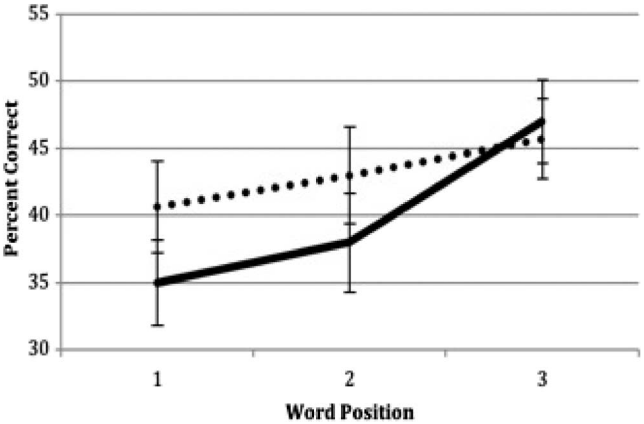
**Table 6.** Summary of stepwise regression analysis for variables predicting Word 3 – Word 1 difference score for the deaf children with CIs.

| Variable | *B* | *SE B* | β | *p* |
|---|---|---|---|---|
| Chronological age | –0.11 | | | .57 |
| Age at implantation | –0.18 | | | .34 |
| Forward Digit Span | –0.07 | | | .72 |
| Backward Digit Span | 0.07 | | | .70 |
| PPVT–III | –0.04 | | | .83 |
| Stroop Color–Word | 0.10 | 0.04 | .52 | < .01 |

*Note.* Adjusted $R^2 = .24$.

As in Experiment 1, to determine whether cognitive control, vocabulary, or digit span abilities predicted performance on the sentence perception task for the children with NH, six hierarchical linear multiple regression analyses were run: one for each of the six word position and type categories (Easy Word 1, Easy Word 2, Easy Word 3, Hard Word 1, Hard Word 2, and Hard Word 3). The independent

**Figure 4.** Percentage accuracy of children with NH for easy (dotted line) and hard (solid line) sentences at each word position (1, 2, and 3). Error bars represent standard errors.



variable added in the first step was chronological age, and all remaining independent variables (Forward Digit Span, Backward Digit Span, PPVT–III raw scores, and Stroop Color–Word raw scores) were added in the second step. The results of the regression analyses showed that the only significant predictor for Easy Words 1, 2, and 3 and for Hard Word 3 was chronological age in the first model. For Easy Word 3, this was a marginally significant effect. For Hard Word 1, age in Model 1 and Forward Digit Span in Model 2 were significant predictors. For Hard Word 2, age in Model 1 was a significant predictor, and PPVT–III in Model 2 was a marginally significant predictor. The full hierarchical regression models for the children with NH are presented in Tables 8 through 13.

Finally, a stepwise linear regression analysis was run for the calculated difference score ($S_{3,1}$). Again, the independent variables were chronological age, Forward Digit Span, Backward Digit Span, PPVT–III raw scores, and Stroop Color–Word raw scores. The results showed that none of the variables that we entered were significant predictors of this difference score.

**Table 7.** Performance of the children with NH on neuropsychological measures.

| Measure | *M* | *SD* | Range |
|---|---|---|---|
| Digit Span | | | |
| Forward | 7.2 | 1.9 | 5–12 |
| Backward | 3.8 | 1.1 | 2–6 |
| PPVT–III | | | |
| Raw score | 117.7 | 22.0 | 87–161 |
| Scaled score | 114.7 | 11.9 | 90–139 |
| Stroop Word | | | |
| Raw score | 58.9 | 15.2 | 29–92 |
| T score | 64.8 | 10.7 | 50–85 |
| Stroop Color | | | |
| Raw score | 37.5 | 8.6 | 21–54 |
| T score | 51.9 | 7.0 | 37–65 |
| Stroop Color–Word | | | |
| Raw score | 21.7 | 5.1 | 12–31 |
| T score | 45.4 | 7.8 | 23–61 |

*Note*. Forward and Backward Digit Span scores are number correct out of 18 total; PPVT–III scaled scores are normed such that a score of 100 represents the mean; Stroop T scores are normed such that a score of 50 represents the mean.

**Table 8.** Summary of hierarchical regression analysis for variables predicting Easy Word 1 for the children with NH.

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | *B* | *SE B* | β | *p* | *B* | *SE B* | β | *p* |
| Chronological age | 0.16 | 0.05 | .48 | < .01 | 0.06 | 0.09 | .19 | .48 |
| Forward Digit Span | | | | | 0.04 | 0.41 | .02 | .92 |
| Backward Digit Span | | | | | 0.86 | 0.65 | .25 | .20 |
| PPVT–III | | | | | 0.04 | 0.05 | .26 | .35 |
| Stroop Color–Word | | | | | –0.03 | 0.13 | –.04 | .82 |
| Adjusted $R^2$ | | .20 | | | | .18 | | |
| $R^2$ change | | .23 | | | | .09 | | |

*Comparison to deaf children with CIs.* Although these analyses are suggestive in that the children with NH, but not the deaf children with CIs, showed evidence of using sentence context to improve spoken word recognition, one concern with relying on the difference scores is that the two groups of children's overall level of word recognition performance was markedly different. Whereas the performance of deaf children with CIs on average was in the 75%–85% range, the children with NH under vocoded degraded conditions actually did much poorer overall, around 35%–45%, which was within the range of performance reported by Eisenberg et al. (2000) for children of this age. Because the overall performance on the sentences is not matched, it is possible that the different amounts of sentence context use that were observed between the two groups could be due to differences in overall performance; that is, perhaps the deaf children with CIs were already doing well enough to preclude any additional benefit from sentence context use, whereas the children with NH were able to make use of sentence context simply because they were starting at a lower overall level of performance.

One way to minimize these differences in overall levels of performance is to assess the gain in performance between the first and third word relative to the maximum possible gain that is possible for that child. Such a calculation

**Table 9.** Summary of hierarchical regression analysis for variables predicting Easy Word 2 for the children with NH.

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | *B* | *SE B* | β | *p* | *B* | *SE B* | β | *p* |
| Chronological age | 0.17 | 0.06 | .49 | < .01 | 0.04 | 0.09 | .12 | .66 |
| Forward Digit Span | | | | | 0.18 | 0.42 | .08 | .67 |
| Backward Digit Span | | | | | 0.33 | 0.62 | .09 | .63 |
| PPVT–III | | | | | 0.07 | 0.05 | .41 | .14 |
| Stroop Color–Word | | | | | –0.05 | 0.13 | –.07 | .70 |
| Adjusted $R^2$ | | .21 | | | | .20 | | |
| $R^2$ change | | .24 | | | | .09 | | |

**Table 10.** Summary of hierarchical regression analysis for variables predicting Easy Word 3 for the children with NH.

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | *B* | *SE B* | β | *p* | *B* | *SE B* | β | *p* |
| Chronological age | 0.10 | 0.05 | .33 | .07 | 0.02 | 0.09 | .07 | .81 |
| Forward Digit Span | | | | | 0.17 | 0.39 | .10 | .66 |
| Backward Digit Span | | | | | 0.48 | 0.63 | .16 | .46 |
| PPVT–III | | | | | 0.03 | 0.05 | .21 | .48 |
| Stroop Color–Word | | | | | 0.001 | 0.12 | .001 | 1.00 |
| Adjusted $R^2$ | | .08 | | | | .01 | | |
| $R^2$ change | | .11 | | | | .07 | | |

has been used, for instance, by Kirk et al. (2012) and for the present case would take the following form:

$$\text{Gain} = S_{3,1}/(20 - \text{W}_1).$$

In this equation, $S_{3,1}$ is the same difference score used earlier (difference between third and first words), and $\text{W}_1$ is the performance on the first word of the sentence. This equation calculates the amount of gain observed from context for each child from the first to the third word position, normalized by the maximum possible gain for that child (out of 20). This gain score therefore takes into account any differences in baseline scores at the first word. For instance, if one child scored 10 on the first words and 15 on the third words, whereas another child scored 15 on the first words and 20 on the third words, their raw difference scores ($S_{3,1}$) would be the same (5). However, they would differ markedly on their gain scores (gain for Child 1 = [15 − 10] / [20 − 10] = 50%; gain for Child 2 = [20 − 15] / [20 − 15] = 100%).

We used this gain score to calculate two gain measures (easy and hard) for each group of children. Any child who started at the maximum performance level of 20 at the first word position was not included in the analysis for that particular measure. The results are presented in Table 14. The results show that whereas the children with NH showed positive gain scores (between 4% and 17%), the deaf children with CIs actually showed negative gains (between −11% and −26%), that is, overall worse performance at the third word compared to the first word in each sentence relative to the maximum possible gain.

**Table 11.** Summary of hierarchical regression analysis for variables predicting Hard Word 1 for the children with NH.

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | *B* | *SE B* | β | *p* | *B* | *SE B* | β | *p* |
| Chronological age | 0.12 | 0.05 | .37 | .04 | –0.02 | 0.08 | –.06 | .83 |
| Forward Digit Span | | | | | 0.83 | 0.37 | .43 | .03 |
| Backward Digit Span | | | | | –0.37 | 0.60 | –.12 | .54 |
| PPVT–III | | | | | 0.06 | 0.04 | .38 | .16 |
| Stroop Color–Word | | | | | –0.07 | 0.12 | –.11 | .53 |
| Adjusted $R^2$ | | .11 | | | | .23 | | |
| $R^2$ change | | .14 | | | | .22 | | |

**Table 12.** Summary of hierarchical regression analysis for variables predicting Hard Word 2 for the children with NH.

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | *B* | *SE B* | β | *p* | *B* | *SE B* | β | *p* |
| Chronological age | 0.17 | 0.06 | .48 | < .01 | 0.02 | 0.09 | .05 | .85 |
| Forward Digit Span | | | | | 0.67 | 0.41 | .31 | .11 |
| Backward Digit Span | | | | | –0.41 | 0.65 | –.11 | .53 |
| PPVT–III | | | | | 0.09 | 0.05 | .46 | .08 |
| Stroop Color–Word | | | | | –0.08 | 0.13 | –.11 | .52 |
| Adjusted $R^2$ | | .21 | | | | .29 | | |
| $R^2$ change | | .23 | | | | .17 | | |

A 2 × 2 analysis was run on the gain scores, with group (children with NH or deaf children with CIs) as the between-subjects variable and sentence type (easy or hard) as the within-subject variable. The analysis showed a significant effect of group, $F(1, 49) = 9.75$, $p < .005$, $\eta_p^2 = .17$, but no effect of sentence type, $F(1, 49) = 0.01$, $p = .92$, $\eta_p^2 = .00$, and no interaction of group by sentence type, $F(1, 49) = 2.40$, $p = .13$, $\eta_p^2 = .05$.

The analyses of the context gain scores suggests that even after taking into account differences in baseline levels, the deaf children with CIs showed little or no use of sentence context, as indicated by negative scores overall, whereas the children with NH showed positive effects of sentence context. Thus, the lack of sentence context use in the deaf children with CIs does not appear to be an age-related effect or a simple consequence of having relatively high baseline scores. Instead, their failure to use sentence context is possibly a result of differences in cognition or language as a result of their hearing history.

## Discussion

The results from this sentence perception study with deaf children with CIs can be summarized as follows. First, Experiment 1 showed that the deaf children with CIs did not use sentence context (i.e., previous words in the sentence) to help them perceive subsequent spoken words in the latter part of each sentence. Rather than performance on each word steadily improving from the beginning of a sentence as we might expect if the children were using

**Table 13.** Summary of hierarchical regression analysis for variables predicting Hard Word 3 for the children with NH.

| | Model 1 | | | | Model 2 | | | |
|---|---|---|---|---|---|---|---|---|
| Variable | *B* | *SE B* | β | *p* | *B* | *SE B* | β | *p* |
| Chronological age | 0.15 | 0.05 | .51 | < .01 | 0.08 | 0.08 | .25 | .35 |
| Forward Digit Span | | | | | 0.15 | 0.36 | .09 | .67 |
| Backward Digit Span | | | | | 0.51 | 0.58 | .17 | .39 |
| PPVT–III | | | | | 0.03 | 0.04 | .22 | .42 |
| Stroop Color–Word | | | | | –0.01 | 0.11 | –.02 | .91 |
| Adjusted $R^2$ | | .24 | | | | .26 | | |
| $R^2$ change | | .19 | | | | .07 | | |

**Table 14.** Comparison of deaf children with CIs and children with NH on gain scores.

| | Deaf children with CIs | | Children with NH | |
|---|---|---|---|---|
| **Measure** | ***M*** | ***SE*** | ***M*** | ***SE*** |
| Gain, easy sentences | –0.11 | 0.10 | 0.04 | 0.08 |
| Gain, hard sentences | –0.26 | 0.10 | 0.17 | 0.08 |

sentence context to facilitate spoken word recognition (and which was demonstrated by the children with NH in Experiment 2), performance for the middle target word was the lowest, similar in shape to the classic serial position curve. The presence of this *U*-shaped curve may indicate a heavy reliance on verbal short-term memory in the task. Second, supporting this account, the regression analyses conducted in Experiment 1 indicated that performance by the deaf children with CIs at each target word was predicted primarily by their verbal short-term memory abilities. On the other hand, Experiment 2 revealed that chronological age, not verbal short-term memory, was the primary predictor of the performance of children with NH at each target word. Furthermore, individual variation in the amount of context gain that the deaf children with CIs displayed from the first to third word (as measured by the difference score, $S_{3,1}$), was predicted by cognitive control abilities, measured by performance on the Stroop Color and Word Test. This last result suggests that deaf children with CIs who have better cognitive control processes are better able to use sentence context to improve their understanding of spoken words. On the other hand, neither cognitive control, nor any other measured variable, predicted the amount of context gain displayed by the children with NH. Finally, Experiment 2 demonstrated that the lack of sentence context use in the deaf children with CIs was not due to their age or to having relatively higher baseline scores. Instead, the lack of sentence context use appears to be a consequence of deafness and/or cochlear implantation that affects their ability to use sentence context to predict and recognize words in sentences.

Before discussing the implications of these findings in greater detail below, we first identify three peculiarities in the results. First, one unanticipated finding is that, unlike the results reported by Eisenberg et al. (2002), the deaf children with CIs did not perform better on the easy sentences relative to the hard ones. Because the easy sentences were composed of words that are both more frequently occurring in natural language and have fewer similar-sounding neighbors in the lexicon, it seems odd that the children did not show better word recognition and reproduction for them. However, the lack of a significant difference here may simply be due to a lack of statistical power. When one examines Eisenberg et al.'s results (see their Figure 5), it appears that the children scored roughly 5% better on sentences with easy compared to hard words. The effect size for the children in our study was comparable, around 3% or 4% better for the easy words at Positions 1 and 3 in the sentence.

A second difference between the results reported here and those of Eisenberg et al. (2002) is that overall, most of the deaf children with CIs in their study demonstrated a beneficial effect of sentence context, whereas, as a group, the children in our study did not. Although the reason for this difference is difficult to know for certain, we believe it is important to recognize that the way that sentence context was operationalized differs between the two studies. Whereas in the present study we operationalized sentence context by examining the difference in performance between Words 3 and 1, Eisenberg et al. measured context by comparing performance for words in sentences versus words in isolation. It is possible then that these two ways of operationalizing sentence context led to different patterns in the data, with deaf children with CIs showing an advantage for words in sentences compared to words in isolation even though, within any given sentence, they might not show a gain in performance between Words 1 and 3 (in contrast to children with NH, who do show such a gain). It is possible that the way we operationalized sentence context in the current study provides a more sensitive measure of processing words in sentences as it unfolds in time and could therefore identify children who are having difficulties with such processing that would not be evident by only comparing words in sentences to words in isolation.

Third, the overall differences between groups on the sentence task is a possible limitation because ideally, to make group comparisons on the use of sentence context, one would want to achieve comparable overall performance across groups on the sentence task. Differences in task performance might differentially recruit different cognitive processes, not due to hearing status but simply due to the difficulty of the task. We attempted to minimize this limitation by incorporating a normalized gain score that takes into account differences in baseline performance. However, another possibility for the future would be to provide extra practice and/or exposure with the spectrally degraded sentence materials for the children with NH. Alternatively, another way to improve the performance of the children with NH would be to use sentences that are not as heavily degraded.

Even with these limitations, we believe the findings present compelling evidence for differences in the ways that deaf children with CIs and children with NH process sentences. The main findings are discussed in more detail below.

## *Processing Sentences as "Strings of Unrelated Words"?*

The present findings revealed that the deaf children with CIs did not show a facilitative effect of sentence context to help perceive words in spoken sentences. This result contrasts with those of earlier studies showing that adults with a hearing impairment use sentence context to compensate for decreased levels of hearing (e.g., Sommers & Danielson, 1999). The failure to use sentence context also contrasts with the results of Experiment 2, which showed that children with NH did in fact use sentence context to facilitate their perception of the final words in sentences that were presented under spectrally degraded vocoded presentation conditions. The lack of sentence context use by the deaf children with CIs in this study is consistent with two earlier studies suggesting that at least some children with hearing impairment may have difficulties making optimal use of sentence context (Eisenberg et al., 2002; Stelmachowicz et al., 2000). Eisenberg et al. (2002) furthermore suggested that some of the children with CIs in their study may have been perceiving each sentence as a "string of unrelated words" rather than an integrated, well-formed, meaningful English sentence.

Consistent with Eisenberg et al.'s (2002) claim for their lowest performing participants, the performance of deaf children with CIs in the current study showed evidence of a serial position effect, with the best performance for the first and last target words of each sentence. Given that the children's word accuracy scores were predicted by verbal short-term memory (as revealed by the regression analyses), it may be fruitful to draw a comparison to the well-known serial position effects in immediate serial recall (Murdock, 1962; Postman & Philips, 1965); that is, if the children were processing each sentence as a string of unrelated words as suggested, then such a process would be heavily dependent on their verbal short-term memory abilities because it entails holding each individual word in memory until it is time to reproduce it. Under this serial memory-based processing account, it therefore makes sense that the sentence perception and reproduction accuracy scores for the deaf children with CIs would resemble the classic serial position curve, with performance best for the initial (primacy effect) and final (recency effect) target words. According to the standard view of serial position effects, the *primacy effect* is due to items being transferred, consolidated, and retrieved from long-term memory, whereas the *recency effect* is due to retrieval of items still being actively maintained in short-term memory (Postman & Philips, 1965). To our knowledge, no other studies that have examined spoken language processing in deaf children with CIs have reported such serial position effects in their sentence perception performance. If this serial memory-based account is correct, then it is important to further explore the roles of sequence memory, learning, and retrieval in this population's ability to understand and process spoken language (see Houston et al., 2012; Pisoni & Cleary, 2004).

On the other hand, rather than a serial memory–based account of this pattern of data, there are other possible alternative interpretations to consider. First, it is possible that the deaf children with CIs did not show a beneficial effect of sentence context because of their relatively lower level of vocabulary knowledge (as indicated by their PPVT–III scores). If a child cannot understand the spoken words at the beginning of a sentence, then this would imply that he or she would be unable to create a meaningful semantic and/or syntactic context on which to help recognize subsequent words in the sentence. Although there is logic to this argument, it is unlikely to be the case with the current findings, for two reasons. One reason is that the words used in the sentences (Eisenberg et al., 2002) are based on the expressive vocabularies of 3- to 5-year-olds, and the deaf children with CIs had a mean receptive vocabulary of 7 years and 5 months, well above the expected level of vocabulary development needed to understand the words in the sentences. A second reason is that the overall level of performance on the target words for the deaf children with CIs was quite high, higher than the children with NH, and yet it was the children with NH, not the deaf children with CIs, who showed a facilitative effect of sentence context. Thus, low vocabulary levels do not appear to be the reason for the lack of sentence context use.

A second possible interpretation is that performance for the deaf children with CIs was lower on the middle word because of differences in coarticulation. Word 1 is sometimes (though not always) the first word of the sentence, and Word 3 is often (though not always) the last word of the sentence, and therefore those two target words would be expected to be coarticulated less and perceived better. If there are perceptual difficulties for the second target word due to coarticulation, it could be that the children were unable to build up a meaningful interpretation of the sentence. However, such a perceptual account cannot explain the present pattern of findings because the deaf children with CIs actually performed much better on the second target word than the children with NH (around 75% vs. roughly 40%), and yet it was the deaf children with CIs, not the children with NH, who showed a lack of sentence context use. For these reasons, we do not believe that lower vocabulary or perceptual difficulties can explain the present findings; instead, they point to different linguistic or cognitive strategies in the ways that deaf children with CIs and children with NH process spoken sentences.

### Separate Influences of Short-Term Memory and Cognitive Control on Sentence Processing

As already discussed, the regression analyses of Experiment 1 revealed a heavy reliance by the deaf children with CIs—but not the children with NH—on verbal short-term memory (and, to a lesser extent, vocabulary knowledge) to help perceive and reproduce each word in a sentence. This result is consistent with a host of other studies that have demonstrated the important role of verbal short-term and working memory in spoken language processing in this population. For instance, Cleary, Dillon, and Pisoni (2002) reported that performance of deaf children with CIs on a nonword repetition task (Gathercole & Baddeley, 1990) was strongly correlated with a number of language outcome measures, including open-set word recognition, speech intelligibility, speaking rate, word attack skills, and rhyme errors. Likewise, Cleary, Pisoni, and Kirk (2002) showed that deaf children with CIs' forward digit spans were significantly correlated with open-set word recognition and receptive language skills. Finally, Dawson et al. (2002) found that performance on short-term memory tasks was significantly correlated with receptive language scores; interestingly, the correlations were much weaker for children with NH, presumably because processing and reproducing spoken language is much less demanding and more highly automatized for them. In the current study, performance of children in the children with NH was most predicted by age alone, perhaps suggesting that this task as well was less demanding and more automatized for them and became even more so with increased age.

On the other hand, the present results show that for deaf children with CIs, the use of sentence context appeared to depend on a different set of cognitive mechanisms altogether. The regression analysis indicated that use of sentence context (gains on Word 3 relative to Word 1) was predicted not by verbal short-term memory but by cognitive control abilities as measured by the Stroop Color and Word Test. None of the other independent variables (chronological age, age at implantation, Forward and Backward Digit Spans, and vocabulary knowledge) were significant predictors of the sentence context scores. This result is consistent with previous research in healthy adults suggesting that language comprehension depends extensively on cognitive control abilities (January et al., 2009; Novick et al., 2005); specifically, using linguistic and extralinguistic contexts is argued to involve cognitive control because the language user must inhibit competing linguistic interpretations and focus on the correct one, which may be even more true when functioning under difficult or adverse listening conditions. As words of an utterance are spoken, the perceiver must update the meaning of the sentence and inhibit previously activated interpretations. Interestingly, recent research with deaf children with CIs has suggested that this clinical population may have disturbances and developmental delays related to exactly these types of cognitive control or executive–organizational–integrative abilities (Beer et al., 2011; Pisoni et al., 2010). Thus, it is possible that the lack of sentence context use observed here is related to delays or difficulties with cognitive control abilities.

In terms of other cognitive processes that may be relevant for understanding spoken sentences, deaf children with CIs also show delays in their statistical-sequential learning abilities, that is, the ability to encode and acquire knowledge about the sequential statistics of environmental stimuli (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011). Recent studies suggest that sequential learning abilities are used to implicitly encode the word order regularities of spoken language and therefore provide the necessary knowledge of language structure to enable appropriate use of sentence context (Conway, Bauernschmidt, Huang, & Pisoni, 2010; Conway, Karpicke, & Pisoni, 2007). Disturbances in sequential learning abilities thus would likely prevent an individual from encoding and representing the fine-grained, temporally based statistical structure of words in spoken language. According to such a view, if a child has difficulties learning about the likelihood of a given word occurring next in a sentence, knowledge that is typically acquired by children with NH in an implicit manner over many years of exposure to language, he or she would be unable to use this information about word predictability to help facilitate spoken language perception. Although the current study does not provide direct evidence for this proposal, disturbances in sequential learning—in addition to delays with cognitive control—may explain why these children were unable to make efficient and optimal use of sentence context to facilitate the perception of words in spoken sentences. Future research will need to specifically examine the possible relations among sequential learning, cognitive control, and sentence context in this population.

Finally, in addition to cognitive control processes and sequential learning, the lack of optimal sentence context use in the deaf children with CIs might be due to a lack of experience with or knowledge of language. Due to receiving a CI an average of 1.75 years after birth, these children have had less exposure to spoken language than their peers with NH. Perhaps the relative lack of language experience leads to selective delays in the use of linguistic knowledge to help perceive the third word in the sentence. It is clear that in general, deaf children with CIs lag behind their hearing peers in language proficiency on numerous measures, including spoken word recognition (Grieco-Calub, Saffran, & Litovsky, 2009), receptive and expressive spoken language processing (Niparko et al., 2010), and knowledge of syntax (Spencer, 2004). What is not clear at this time is the extent to which the use of sentence context depends on previous language experience or ability. Certainly, some aspects of language use are dependent on previous linguistic experience. However, our regression analysis revealed that inhibitory cognitive control processes (as measured by the Stroop test), not vocabulary scores (as measured by PPVT–III) predict sentence context use. Thus, the current findings do not provide evidence to support the notion that language experience (or the lack thereof) influences the ability of children to optimally use sentence context to perceive spoken words in sentences. On the other hand, this study included only one assessment measure of language (PPVT–III); it is possible that other aspects of language (e.g., syntactic knowledge) might be more related to the use of sentence context. For example, perhaps a lower level of proficiency with syntax leads to a decreased ability to use syntactic information to help facilitate the processing of subsequent words in a sentence. Future research might profitably explore the possible interactions between language experience and cognitive factors in contributing to the ability to use sentence context.

These present findings provide some preliminary support for the proposal of two separate cognitive influences on sentence processing in deaf children with CIs: Verbal short-term memory abilities are used to encode, remember, and retrieve each word in a sentence, whereas cognitive control abilities enable the use of sentence context to help recognize and understand the final word in each sentence. Delays to domain-general cognitive control abilities (Beer et al., 2011; Pisoni et al., 2010) or basic learning mechanisms (Conway et al., 2011) might explain why, as a group, these children showed a lack of ability to use sentence context to perceive speech.

## *Conclusions*

This study has uncovered several important new findings about the sentence processing skills of deaf children with CIs. Rather than using sentence context to optimally help facilitate the perception and understanding of words in a sentence, deaf children with CIs as a group appear to process each sentence as if it were a simple string of unrelated words. Possibly because of delays or disturbances to underlying domain-general cognitive control processes that go beyond the language domain (Beer et al., 2011), these children may be unable to successfully select from among various competing interpretations of the final word in a sentence. In turn, such an inability to utilize sentence context to improve speech perception for the last words in a sentence puts a heavy demand on immediate verbal memory capacity, resulting in a serial position curve, in which performance is poorest for the middle words of a sentence. The evidence from the present study suggests that, as a group, these children appear to encode and process spoken sentences "as strings of unrelated words" (Eisenberg et al., 2002), not having a good sense of how various words co-occur with others in a given sentence context and being unable to use previous words to help perceive and recognize subsequent ones. These findings suggest several new avenues to better understand the language learning and processing disturbances of deaf children with CIs by focusing on basic underlying neurocognitive processes of learning, memory, and cognitive control that are necessary prerequisites for recognizing and understanding spoken words in meaningful sentences.

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## Appendix

Test Sentences From Eisenberg et al. (2002). Reprinted with permission from Wolters Kluwer Health.

Each sentence contains three key words (in italics).

Lexically easy sentences

1. That *kind* of *airplane* is *brown*.
2. You can't *stand* on your *broken truck*.
3. The *children cried* at the *farm*.
4. I *broke* my *finger* at *school*.
5. My *friend thinks* her *lipstick* is cool.
6. *Give* the *monkey* some *juice*.
7. I can *wash* the *ducks myself*.
8. I can *draw* a *little snake*.
9. *Open* the *green* one *first*.
10. The *string* can *stay* in my *pocket*.
11. *Please help* her with the *puzzle*.
12. *Don't scribble* on the *door*.
13. I saw *seven eggs* in the *street*.
14. I *just* found the *grey shoelace*.
15. I *wonder* who *brought* the *food*.
16. I know *which space* is *black*.
17. *It's* always fun to *watch* the *fish*.
18. *Let's* buy *gas from* that man.
19. I hope the *girl takes* some *milk*.
20. The chair could *break when* I *jump*.

Lexically hard sentences

1. *Tell* him to *sleep* on his *belly*.
2. The *bunny hid* in my *room*.
3. She *likes* to *share* the *butter*.
4. His *son played* with the *chickens*.
5. Call if you *ever find* the *toys*.
6. *Grampa laughed* at the *goats*.
7. *Dad came* to say *hello*.
8. The *boys* took *turns locking* the car.
9. *Many kids* can *learn* to sing.
10. She *lost* her *mommy's ring*.
11. She *knows* where to *leave* the *money*.
12. The *piggy moved* the *books*.
13. The *gum* is in the *tiny box*.
14. His *tummy* hurt for *ten days*.
15. *Start walking* to your *seat*.
16. He *taught us* that funny *trick*.
17. The *worm* was *stuck* in the *pool*.
18. I *guess* you *were* in the *rain*.
19. The *cups* are in the *pink bag*.
20. *Both* of the naughty *cats* are *mine*.