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The Effect of Sentence Length on Question Comprehension in Children with Cochlear Implants

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Abstract

Objectives: The present study investigated the comprehension of subject and object *who* and *which* questions in children with cochlear implants (CI).

Methods: Using eye tracking, we compared fixations and gaze patterns to the appropriate subject or object noun between 16 children with CI and 31 children with typical hearing (aged 7;0-12;0) on wh-questions with and without added adjectives to increase length. Growth Curve Analysis (GCA) was used to compare fixations and gaze patterns between groups over a four-picture array. Comparisons of offline accuracy were also conducted.

Results: Findings indicated children with typical hearing exhibited more fixations to the target noun across all conditions, supporting higher comprehension accuracy. Both groups of children demonstrated more fixations to the target noun in object questions and questions without added length. Patterns of eye movement were significantly different between groups, suggesting different patterns of eye gaze across the array before fixation on the target noun. Children with CI exhibited fewer fixations, slower speed to fixation, and differences in gaze patterns that may imply the presence of processing limitations. Error analyses also suggested that children with CI frequently fixated on a picture similar to the target noun.

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Declaration of interest
The authors have no conflicts of interest in regards to the research presented in this article.

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Conclusions: Results indicate children with CI comprehend questions more slowly than their hearing peers, which may be related to limitations in working memory.

Keywords

cochlear implants; language acquisition; language processing; eye tracking

Introduction

Many children with cochlear implants (CI) are able to achieve typical, though highly variable, language growth trajectories (Niparko et al., 2010). Nevertheless, deficits in spoken language comprehension may persist as a result of prolonged periods of deprivation and modified hearing access. One such area of difficulty is complex syntax comprehension, including poor comprehension and production of wh-questions (Friedmann & Szterman 2005, 2011; Fujiyoshi et al. 2012; Geren 2010). Wh-questions are thought to be more challenging to comprehend because of variation from the canonical form of Subject-Verb-Object (SVO, e.g., Gibson, 1998). Subject questions (e.g., *Who saw Maria*?) maintain their subject-verb-object (SVO) structure, even as "*Who*" replaces the subject of the sentence (e.g., *Susie saw Maria*). In object-subject-verb (OSV) sentences, like object questions (e.g., *Who did Susie see?*), "*Who*" replaces the object of the sentence and is fronted to the beginning of the question. When the wh-question word serving as object occurs in the first, and assumed subject, position, sentence nouns must be stored in memory while the sentence is comprehended (e.g., Gibson, 1998), adding memory processing demands to comprehension processing demands. If memory is compromised in language processing, the ability to comprehend the sentence may also be negatively impacted.

Poor wh-question comprehension in children with cochlear implants

Previous literature using picture-pointing tasks (e.g., Friedmann & Szterman, 2011; Ruigendijk & Friedmann, 2017) framed the difficulties children with hearing loss (HL) have in comprehending object wh-questions (OSV word order) as a result of poor thematic role assignment. Thematic role assignment is the determination of the semantic role of a noun in a sentence. In SVO sentences, the agent (subject) and the theme (object) nouns within a sentence occur linearly. In contrast, sentences with OSV word order have a nonlinear thematic role noun order and thus, require full comprehension of the sentence to assign thematic roles correctly. Yet these studies (Friedmann & Szterman, 2011; Ruigendijk & Friedmann, 2017) purported to evaluate role assignment, and employed a choice between two pictures: one depicting accurate thematic roles and one depicting reversed thematic roles. Thus, errors were automatically considered failure of role assignment.

The effect of added length in question comprehension

To further investigate the poor thematic role assignment suggested in children with CI, Schouwenaars et al. (2019) explored the eye movements of German-speaking children with CI as they listened to subject and object *which* questions. Patterns of eye movement in subject questions with SVO word order were similar between children with CI and children with typical hearing. However, Schouwenaars et al. (2019) found that eye gaze

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differed between groups in object *which* questions. Object *which* questions, that are more complex and potentially longer, are more difficult to comprehend for children with typical language development (Roeper & De Villiers, 2011). *Which* questions with certain verbs are longer than *who* or *what* questions because they include a second noun phrase (e.g., *Which grandma was kissed by the boy?*), and may contribute to the increased difficulties in comprehension observed in *which* questions as compared to *who* questions (Gordon, Hendrick & Johnson, 2004). Sentences with increased length may also increase demands on working memory resources, which are limited in both children and adults (King & Just, 1991; Gaulin & Campbell, 1994). Moreover, increased sentence length may further compound the demands of thematic role assignment in OSV sentences. A second multiword noun phrase may increase distance between the object noun and its typical location following the verb, as found in object questions (Traxler et al., 2002), and creates a need to select an answer from two or more possibilities. And so, Schouwenaars et al.'s (2019) eye gaze data from object questions with OSV word order found children with CI demonstrated fewer fixations on the picture that accurately depicted the question than their hearing peers. In addition, children with CI were slower to fixate on the picture that accurately matched the question, and exhibited more gazes towards the picture that depicted reversed thematic roles.

Working memory in children with cochlear implants

Schouwenaars et al. (2019) also conducted forward and backward digit span tasks to examine correlations between short-term memory (STM) performance and wh-question comprehension. They found a correlation between scores on backwards digit span and mean accuracy scores in object which question comprehension. This correlation suggests a link between STM abilities and wh-question comprehension in children with CI. However, this link could not be established when correlating nonword repetition scores and wh-question comprehension in children with HL (Penke & Wimmer, 2018). Short-term memory tasks, like digit span and nonword repetition, may only identify issues with storage of items in memory and may not adequately reflect how memory is used in language processing. Working memory is likely more reflected in tasks where items are simultaneously stored, processed, and integrated with other information (Kyllonen & Christal 1990; Conway et al. 2002; Cowan 2008).

Newer views of working memory include interference (Miyake & Shah 1999) as a possible explanation for capacity limitations. Interference describes the displacement of similar or competing items held in working memory simultaneously (e.g., Van Dyke & McElree 2006), which adversely affects their retrieval. Increased length and the presence of a second noun phrase may expedite the exhaustion of capacity and also exacerbate interference effects, negatively impacting sentence comprehension accuracy (Van Dyke & Johns, 2012). The increased memory demands of comprehending longer wh-questions, especially object questions, may influence comprehension accuracy in children with CI.

The present study

We investigated the effect of sentence length on subject and object *who* and *which* question comprehension in children with CI in a visual world eye tracking paradigm. Deevy and Leonard (2004) found that children with Developmental Language Disorder

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(DLD) comprehended short subject and object questions with similar accuracy to receptive vocabulary-matched peers. However, different rates of accuracy emerged when two adjectives were added to subject and object questions. In addition to increasing overall sentence length, the two added adjectives were thought to increase working memory demands. The additional adjectives extended the distance between the wh-question and the object noun in object questions with OSV word order. Comparison between groups revealed the children with typical language development to maintain their accuracy in both subject and object questions despite the additional adjectives, while children with DLD performed more poorly on object questions with increased length. Other studies have reported similar findings on the relationship between sentence length, sentence complexity (especially sentences without SVO structure), and decreased comprehension accuracy in children with DLD and further connected it to performance on complex span memory tasks (e.g., Marton et al., 2006; Montgomery & Evans, 2009; Montgomery et al., 2018). Most recently, Delage and Frauenfelder (2020) found performance on short-term memory (STM) tasks and complex span tasks predicted accuracy in comprehension and repetition of subject relatives and object relatives in French-speaking children with DLD. As subject relatives and objective relatives in French have identical sentence structure to subject questions (SVO) and object questions (OSV) in English, these results are not surprising. However, this overt link to STM and working memory warrants investigation in other populations with poor STM and working memory including children with CI. Children with HL have demonstrated poor memory skills, namely STM, when compared to hearing peers. Burkholder & Pisoni (2003) reported a significant 3-digit difference in forward and backward digit span scores between children with CI and children with typical hearing. Similar differences in digit recall have been reported in other studies (Pisoni & Cleary, 2003; Geers et al., 2013; Soleymani et al., 2014). Children with CI have also demonstrated difficulties in nonword repetition tasks when compared to their hearing peers (Penke & Wimmer, 2018). Variability has also been indicated in visual sequencing tasks, however the relationship to audition is unclear (Conway et al., 2009; Conway et al., 2011; von Koss Torkildsen et al., 2018). The previously mentioned measures assess STM with single word linguistic stimuli, thus it bears investigating how increased memory demands in the form of added words might play a role in their comprehension of wh-questions.

We presented subject and object *who* and *which* questions in two conditions. The first condition was a short question condition (e.g., *Which grandma is kissed by the boy before school?*). The second condition included two additional adjectives attached to the noun phrase(s) present in the question (e.g., *Which kind, happy grandma is kissed by the silly, little boy before school?*) to increase sentence length. In addition, four pictures were presented in an eye tracking and picture selection (mouse click) paradigm to allow error analyses. Observation of eye movement as children listened to questions and selected the appropriate picture provided insight into three hypotheses:

(1) When compared to age-matched peers with typical language development, children with CI would demonstrate fewer gaze fixations and slower time to fixation on the noun that answered the wh-question in questions with OSV sentence structure (object questions).

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(2) When compared to age-matched peers with typical language development, children with CI would demonstrate fewer fixations and slower time to fixation on the noun that answered the wh-question in *which* questions, given the presence of a second multiword noun phrase.

(3) Children with CI would demonstrate fewer fixations and slower time to fixation on the noun that answered the wh-question in questions with added length, demonstrating more susceptibility to working memory limitations than their age-matched peers with typical language development.

Given the evidence supporting poor memory skills in children with HL, it is crucial that we begin to understand how memory may affect their wh-question processing in real time. Difficulty with complex syntactic structures, particularly wh-questions, may severely impact academic achievement because of their frequent occurrence in classroom discourse (Cotton, 1988). Confirmation of these hypotheses would suggest the presence of underlying language comprehension difficulties that may be related to working memory limitations in children with CI and support improved assessment and intervention strategies.

Materials and methods

Participants

This study was approved by the Institutional Review Boards of the Graduate Center of the City University of New York, the New York Eye and Ear Infirmary, and the Indiana University School of Medicine. Forty-seven children were recruited. Participants included 31 children with typical hearing who ranged in age from 7;4-11;11, with a mean age of 9;11 (SD = 1;5), and 16 CI recipients recruited from outpatient audiology practices who ranged in age from 7;11-11;10 years, with a mean age of 9;10 (SD = 1;4). Children with CI were implanted by 5;0, with a mean age at implantation of 2.7 years (SD = 1;8). Years of experience using their devices ranged from 4;6-10;1, with a mean of 7;4 years (SD = 1;8). The CI users included 10 bilateral users, 1 unilateral user, and 5 bimodal CI and hearing aid users.

All 47 participants passed a soundfield hearing screening at 30 dB in their best aided condition and completed behavioral testing. Behavioral testing included the Test of Nonverbal Intelligence, 4th Ed. (TONI; Brown et al., 2010), the Peabody Picture Vocabulary Test, 4th Ed. (PPVT-4; Dunn & Dunn, 2007), and the Core Language portion of the Clinical Evaluation of Language Fundamentals, 4th Ed. (CELF-4; Semel et al., 2003). A series of independent t-tests found the children with typical hearing had significantly higher scores than children with CI on the TONI-4 ($t(48) = -3.12$, $p = .003$), the PPVT-4 ($t(21.74) = -3.539$, $p = .002$), and in core language scores on the CELF-4 ($t(16.05) = -4.27$, $p = .001$). A parent questionnaire was administered to collect demographic data on participants. Subject data is displayed in Table 1.

Stimuli and Procedures

Eighty pre-recorded wh-questions were presented at 55 dB to simulate conversational speech level (Clark & Martin, 2019) in a soundproof audiology suite. Auditory stimuli were presented via overhead speaker to the participant, along with four pictures per question

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presented on a Tobii T-60 Eye Tracking monitor networked to two PC. Subjects' eye gaze, movement, and position were calibrated to the equipment. Each question was preceded by one of 20 context sentences with similar syntactic structures. The 80 questions were divided among subject and object questions, *who* and *which* questions, and short and long conditions. Long condition wh-questions had two added adjectives per noun phrase. This served to increase both sentence length and sentence complexity, and subsequently increase demands on working memory.

Context sentences and questions included only animate nouns. Questions were presented in 10 blocks of 8 pseudorandomized trials, containing all of the 8 possible question types (*subject who short*, *subject who long*, *subject which short*, *subject which long*, *object who short*, *object who long*, *object which short*, and *object which long*) with each context sentence appearing only once per block. We randomized the order of these blocks and the trials within each block, with a total presentation time of 45 minutes. The children were instructed to listen to the sentence and the question, and then use the mouse to click on the picture that answered the question. During presentation of the context sentence, the computer screen remained blank. Four pictures appeared over a green background 750 milliseconds (ms) prior to the presentation of the wh-question. The picture array included: the subject of the question, the object of the question, an attribute foil, and a noun foil. The attribute foil differed from the target noun only in a defining attribute (e.g., if the target noun was a grandma with grey hair, the attribute foil depicted a grandma with blonde hair). The noun foil differed from the target noun only in the noun depicted (e.g., if the target was a grandma with grey hair, the noun foil would be a man with grey hair). Positions of the target and foil pictures were randomized across trials. An example of this array is visible in Figure 1.

Once the wh-question had been presented, the child was given as much time as needed to answer via mouse click with a fixation cross presented prior to the start of the next trial. Question comprehension via mouse click was recorded in E-Prime (Psychology Software Tools, 2012) and served as an offline measure of wh-question comprehension accuracy. Eye gaze data were collected for 3700 ms (the duration of the longest sentence from the onset of the sentence) by the Tobii and E-Prime software and were analyzed by a custom MATLAB program. Gaze data from accurate trials were analyzed in MATLAB to identify fixations, defined as looks longer than 50 ms, to the presented picture stimuli.

Results

Offline Accuracy

Accuracy percentages derived from mouse-click data are presented in Table 2. Question response accuracy was examined in a mixed ANOVA with group as a between-subjects variable and question types (short and long conditions, subject and object questions, *who* and *which* questions) as repeated measures, within-subjects variables. There was a significant main effect of group ($F(1,45) = 12.412$, $p = .001$), as children with typical hearing (83.8% accuracy, SD = 11.9) displayed significantly greater accuracy than children with CI (68.8% accuracy, SD = 16.3). There was also a significant main effect of sentence length, with higher accuracy observed in short condition questions ($F(1,45) = 6.552$, p =

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.014). A significant two-way interaction was observed between object and subject questions and *who* and *which* questions ($F(1,45) = 8.000$, $p = .007$). Post-hoc Tukey tests showed subject *which* questions to have significantly lower accuracy than subject *who* questions ($p = 0.058$).

We also found a significant three-way interaction among the three question variables: short/long condition, object and subject questions, and *who* and *which* questions ($F(1,45) = 4.984$, $p = .031$). Post-hoc Tukey tests indicated that object *who* questions in the long condition had significantly lower accuracy than subject *who* questions in the long condition ($p = 0.028$). Post-hoc Tukey tests did not reveal significant differences in other comparisons.

Eye Tracking Results

Growth-curve analyses (GCA; e.g., Mirman 2017) conducted on gaze data collected across the time courses of wh-questions allowed for comparisons between question types and groups, and within-group comparisons. A subtype of linear mixed-effects models (Winter & Wieling, 2016), GCA was used to explore differences in fixation proportions to the target picture across each trial, with time courses determined by longest question length (3700 ms) across conditions. Four separate growth-curve models were used to examine eye gaze behavior by question type (model one), between groups (model two), and within groups (typical hearing and CI, models three and four respectively). Models one, three, and four were fit using third-order orthogonal polynomials with comparison pairs by question condition including Question Type (Subject/Object), Question Word (*Who/Which*), and Question Length (Short/Long) as fixed effects and average group performance of participants and participants-by-pair. Model 2, the between-group model, was fit using third-order orthogonal polynomials that included group and comparison pairs by question type as fixed effects and random effects of participants and participant-by-pair. P-values were estimated using the normal distribution. In these growth-curve models, the intercept (b_0) term describes the proportions of fixation to the correct pictured noun and the linear (b_{Time}) term describes time to fixation on the correct pictured noun. Quadratic (b_{Time2}) and cubic (b_{Time3}) terms describe patterns of eye gaze fixations over the time course of the trial. They convey information on gaze to other pictures in the array prior to fixation on the target noun. Results from Model Two comparing eye gaze between typical hearing and CI groups is displayed in Figure 2. Growth-curve analyses results from all models are also presented in Tables 3–6.

Hypothesis 1

We hypothesized that children with CI would demonstrate fewer fixations and slower time to fixation to the target noun in object questions. This hypothesis was not confirmed.

Results from Model One.—Analysis by question type revealed a main effect of group, as children with typical hearing showed significantly increased proportion of fixations ($b_{Group} = 0.056$, $SE = 0.023$, $p = 0.014$) to the target noun across all question conditions.

Results from Model Two.—A main effect of group indicated children with CI showed fewer proportions of fixations to all question types ($b_{Group} = 0.052$, $SE = 0.026$, $p =$

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0.045) in comparison to children with typical hearing. No significant group-by-question type interaction effects were found, suggestive of a similar time course of gaze behavior between groups.

Results from Models Three and Four.—Within group models found significant main effects of question type that indicated increased proportions of fixations to the target noun in object questions in both groups (children with typical hearing: $b_{QuestionType} = 0.133$, $SE = 0.012$, $p < 0.001$; children with CI: $b_{QuestionType} = 0.131$, $SE = 0.020$, $p < 0.001$). Within children with typical hearing, a main effect of question type indicated faster time to fixation on the target noun in object questions ($b_{Time\ x\ QuestionType} = -0.387$, $SE = 0.142$, $p = 0.006$), while the within group model for children with CI showed no difference in time to fixation between question types. Within group models found a significant effect of question type on patterns of eye gaze over time in both groups (children with typical hearing: $b_{Time2\ x\ QuestionType} = -0.251$, $SE = 0.102$, $p = 0.013$; children with CI: $b_{Time2\ x\ QuestionType} = -0.611$, $SE = 0.168$, $p < 0.001$), which indicated gaze behavior over the time course of the question was distinctly different between object and subject questions. This suggests that the process of determining where to fixate (i.e., the target noun) was different between object and subject questions.

Hypothesis 2

We hypothesized that children with CI would demonstrate fewer fixations and slower time to fixation to the target noun in *which* questions. This hypothesis was confirmed.

Results from Model One.—A main effect of question word was found across groups with increased proportion of fixations to the target in *who* questions ($b_{QuestionWord} = 0.104$, $SE = 0.012$, $p < 0.001$). A significant effect of question word on patterns of eye gaze over time revealed differences in gaze behavior between *who* and *which* questions across groups ($b_{Time2\ x\ QuestionWord} = -0.203$, $SE = 0.102$, $p = 0.047$).

Results from Model Two.—Group-by-question type interactions indicated children with typical hearing exhibited significantly more proportions of fixations ($b_{QuestionWord\ x\ Group} = 0.067$, $SE = 0.024$, $p = 0.005$) and faster time to fixation ($b_{Time\ x\ QuestionWord\ x\ Group} = -0.623$, SE = 0.220, p = 0.005) towards the target noun than children with CI in *who* and *which* questions. Significant interaction was also found between question word and group when modeling patterns of eye gaze over time ($b_{Time2\ x\ QuestionWord\ x\ Group} = -0.053$, $SE = 0.213$, $p = 0.013$), which suggests the groups differed in their looks to determine and fixate on the correct noun between *who* and *which* questions.

Results from Models Three and Four.—Results from within group models supported the results of Model One, with both groups of children featuring increased proportion of fixations to the target in *who* questions (children with typical hearing: $b_{QuestionWord} = 0.126$, $SE = 0.012$, $p = 0.000$; children with CI: $b_{QuestionWord} = 0.06$, $SE = 0.024$, $p = 0.014$). Within group models also indicated a significant effect of question word on patterns of eye gaze over time in children with typical hearing ($b_{Time2\ x\ QuestionWord} = -0.383$, $SE = 0.109$,

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$p = 0.000$), while the only significant effect of question word in children with CI was faster time to fixation in *who* questions ($b_{Time\ x\ QuestionWord} = 0.545$, $SE = 0.212$, $p = 0.010$).

Hypothesis 3

We hypothesized that children with CI would demonstrate fewer fixations and slower time to fixation to the target noun in questions with added length. This hypothesis was confirmed.

Results from Model One.—A main effect of question length was found across all participants with increased proportions of fixations in short questions than long questions ($b_{QuestionLength} = -0.044$, $SE = 0.009$, $p < 0.001$). There was also a significant effect of question length on time to fixation, with faster time to fixation in short questions overall ($b_{Time\ x\ QuestionLength} = -0.814$, $SE = 0.094$, $p < 0.001$).

Results from Model Two.—Children with typical hearing demonstrated significantly increased proportions of fixations across question lengths when compared to children with CI ($b_{Group} = 0.055$, $SE = 0.024$, $p = 0.025$), suggesting sentence length may have a greater impact on question processing speed in children with CI. There was significant interaction between question length and group when modeling eye gaze patterns over time ($b_{Time3\ x\ Question\ Length\ x\ Group} = 0.364$, $SE = 0.150$, $p = 0.016$), suggesting groups differed in their looks to determine and fixate on the target noun in short and long questions.

Results from Models Three and Four.—Results from within group models supported the results of Model One, with both groups of children featuring increased proportion of fixations (children with typical hearing: $b_{QuestionLength} = -0.042$, $SE = 0.01$, $p = 0.000$; children with CI: $b_{QuestionLength} = -0.046$, $SE = 0.017$, $p = 0.006$) and faster time to fixation to the target (children with typical hearing: $b_{Time\ x\ QuestionLength} = -0.883$, $SE = 0.098$, $p = 0.000$; children with CI: $b_{Time\ x\ QuestionLength} = -0.68$, $SE = 0.185$, $p = 0.000$) in short questions. Within group models also indicated a main effect of question length in patterns of eye gaze over time in children with typical hearing ($b_{Time2\ x\ QuestionLength} = 0.212$, $SE = 0.101$, $p = 0.036$, $b_{Time3\ x\ QuestionLength} = 0.563$, $SE = 0.075$, $p = 0.000$), suggestive of differences in looking behavior by question length. This effect was not present in children with CI.

Error Analyses

Due to the small number of errors (see Table 2 for accuracy data), eye gaze data from questions answered incorrectly by mouse click were examined descriptively. While no discernable patterns were present in mouse click data from inaccurate trials, eye tracking data revealed error patterns that differed across groups. Fixation proportions for each of the pictures in the array were derived from MATLAB analyses over the time course of the longest question (3700 ms). In subject questions with incorrect answers, all children regardless of group had the highest proportions of fixations towards the object of the sentence, .38 and .32 respectively, with the remaining fixations distributed among the other pictures in the array. As they were expected to fixate more on the subject noun in subject questions, high proportions of fixation to the object picture indicate role reversal (incorrect thematic role assignment). In object questions with incorrect answers, the highest proportion

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of fixations of children with typical hearing, .28, were directed towards the correct object noun, despite incorrectly answering the question via mouse-click. In contrast, children with CI directed their highest proportion of fixations, .33, to the attribute foil of the target object noun. This finding suggests that children with CI frequently fixated on the picture most similar to the target noun in error trials. We note that this indicates an absence of perceptual confusions between foils with acoustically similar labels (e.g., grandma versus grandpa).

Discussion

While findings from our offline measures were similar to earlier offline findings (Geren, 2010; Ruigendijk & Friedmann, 2017), results from eye tracking data revealed differences between groups that may enrich our understanding of how children with CI comprehend wh-questions. Children with CI had significantly poorer question accuracy than their hearing peers. We found slightly more accurate question comprehension by children with CI than in previous studies (Geren, 2010; Ruigendijk & Friedmann, 2017), a finding that may be attributed to improvements in intervention or the implant itself. Through eye tracking, we observed children with typical hearing to exhibit more fixations towards the correct noun during wh-question processing than their counterparts with CI overall. This finding is in agreement with their higher offline accuracy. The relatively small number of children with CI, and significant differences in the baseline language abilities of the children with CI in comparison to their age-matched hearing peers may have accounted for some of the findings. With 16 participants with CI, our ability to examine within-group differences (such as age at implantation or language assessment scores) on performance was limited. It should also be noted that this study reflects the performance of children with CI with relatively later average age of implantation (2;7 years), which may negatively impact spoken language comprehension and perceptual skills (Karltorp et al., 2020). Bimodal device users were also included in this study, which may also contribute to differences in perception and language development (Davidson et al., 2019). However, this variability may not be uncommon in children with CI receiving intervention, and thus, the differences in performance are discussed below.

Differences between subject and object questions

Our first hypothesis was not confirmed. Both groups of children had more fixations to the target noun in object questions than in subject questions. Both groups also displayed significantly different patterns of looking behavior between subject and object questions, suggestive of different processing patterns between subject and object questions. This finding supports the fact that sentences with SVO structure (i.e., subject questions) and sentences with OSV structure (i.e., object questions) have unique cognitive and linguistic demands (Gibson, 1998; Deevy & Leonard, 2004).

Group was not a predictor of number of fixations or time to fixation in either subject or object questions. These findings suggest that children with CI are capable of determining whether a sentence has SVO or OSV word order and adjusting sentence interpretation accordingly. This is unlike previous findings from Schouwenaars et al. (2019), who found that children with CI persist in SVO role assignment for object questions in German (where

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case markings denote thematic roles). This discrepancy suggests that the children with CI studied in Schouwenaars et al. (2019) were more affected by case marking information than their screening measure would suggest, or it may be due to our study's single noun pictures (Schouwenaars et al.'s pictures also included the action). Our finding suggests that children with CI process object questions similarly to their hearing peers, within the context of poorer overall accuracy and processing differences revealed by eye gaze. For example, children with typical hearing exhibited more fixations and were faster to fixate on the correct noun in object questions than children with CI. This suggests slower recognition of the correct noun and slower integration of sentence constituents.

Differences between who and which questions

In comparison to their age-matched, hearing peers, children with CI had fewer fixations to the target noun and required more time to fixate on the target noun in both *who* and *which* questions. Again, this is indicative of generally slower processing for wh-questions in the CI population. As we hypothesized, the only significant group difference found between *who* and *which* questions was found in their patterns of looking during question processing. Differences in patterns of gaze behavior while listening to the question revealed that children with CI fixated on different pictures than their hearing peers prior to fixating on the target noun. This indicates children with CI not only needed more time to process the question, but they also spent more time looking at different pictures than their hearing counterparts to determine the correct noun. Although differences in looking behavior may have been related to acoustic similarities in the labels for some of the foils (e.g., grand*ma* vs. grand*pa*), fewer than five questions featured items with acoustic similarities and the error data suggests that this was not the case. This difference in looking behavior is more likely to reflect the working memory challenges posed by the presence of a second noun phrase (Traxler et al., 2002; Gordon et al., 2004) and its likelihood to introduce interference in populations with compromised capacity (Van Dyke & Johns, 2012) such as children with CI.

Differences between short and long questions

Based upon Deevy & Leonard's (2004) study in children with DLD, we manipulated the length of wh-questions by adding two adjectives to the noun phrase(s). As sentence length was identified as a factor contributing to poor comprehension of complex syntax in children with DLD, who also exhibit poor STM and working memory skills (Deevy & Leonard, 2004; Marton et al., 2006; Montgomery & Evans, 2009; Montgomery et al., 2018), our third hypothesis suggested that sentence length also contributed to poor comprehension in the CI population. Both groups of children demonstrated fewer target fixations and slower speed to initial fixation on the target noun in questions with extended length, and exhibited different patterns of looking behavior between short and long questions. Even acknowledging the extended time for looking during longer questions, the gaze difference across the array between short and long questions may mean sentence length and added working memory demands due to the assumed presence of linguistic movement, affected sentence comprehension and processing in both groups. This supports the offline comprehension findings that indicated poorer accuracy for longer questions in both groups, especially when the length was added to an object question. Yet, children with typical hearing had more fixations to the correct noun and were significantly faster to fixate

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on the correct noun than their peers with CI in the longer sentences. The similarities in patterns of looking behavior and offline accuracy for sentences with added length suggest that children with CI are developing approaches to processing wh-questions with varying memory demands. Yet with fewer and slower fixations to the target noun, more research is needed to understand how increase memory demands may affect children with CI, especially with regard to additional auditory processing efforts noted in theories such as the *Framework for Effortful Listening* (Pichora-Fuller et al., 2016).

The unexpected finding that children in both groups looked more at target in object questions may well have been evidence of interference. The children's comprehension may have been facilitated by the presence of a similar looking noun, the attribute foil. This may have had an asymmetrical effect on object wh-questions than subject wh-questions, as the target noun is represented in two places, which is unlike previous studies.

Error Analyses

Whereas previous studies only included two images containing either correct or reversed thematic role assignment (Friedmann & Sztermann, 2011; Ruigendijk & Friedmann, 2017; Schouwenaars et al., 2019), we gathered data on incorrectly comprehended wh-questions with a four-picture array that included the target subject or object, the non-target subject or object, an attribute foil, and a noun foil. Qualitative examination of fixation proportions towards non-target pictures in the array provided insight into the particular foils the children fixated on in these trials. Both groups of children exhibited role reversal in incorrectly answered subject questions with SVO structure with the highest fixation proportions to the object noun. A different pattern was observed for errors on object questions with OVS structure. Children with typical hearing had the highest fixation proportions to the correct object noun, suggesting accurate role assignment. In contrast, children with CI had the highest proportion of fixations on the object attribute foil during error trials of object questions. This finding further supports the ability of children with CI to assign thematic roles in OVS sentences correctly. While previous studies only provided two pictures, our study's use of four pictures introduced competition between the attribute foil (e.g., a boy in a red shirt) and the target (e.g., a boy in a blue shirt). It may be that fixations towards a competitor indicate increased memory demands, possibly due to interference, negatively impact thematic role assignment in children with CI.

Summary

Similarities in patterns of looking relative to their hearing peers and increased offline accuracy in comparison to previous studies suggest that aspects of wh-question processing that are near typical in the CI population. Yet other results appear to tell a different story; children with CI face challenges greater than thematic role assignment in their wh-question comprehension. These challenges may be further exacerbated by later implantation and variable language performance, as was observed in our group of children with CI. The significantly higher number of fixations and speed to fixation in children with hearing suggests slowed processing and complications with reintegration of sentence parts in children with CI. Patterns of fixation identified in *who* and *which* questions that diverge from their hearing peers, increased susceptibility to poor comprehension

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due to sentence length, and results from error analyses in children with CI appear to suggest that impoverished working memory skills play a role in their wh-question comprehension. Our results more concretely support the correlation between object *which* question comprehension accuracy and backward digit span in children with CI identified in Schouwenaars et al. (2019) by establishing a link between comprehension and working memory demands within the sentence itself. Difficulty integrating a second noun phrase or fixating on the correct noun over an extended time in children with CI may be attributed to poor resistance to interference, which may negatively affect both working memory performance and language comprehension (Gordon et al., 2001). Whether these findings reflect poor resistance to distractor interference and/or proactive interference (Friedman & Miyake, 2004) is not clear. Children with CI might have been distracted by the linguistic and visual similarities between the pictures (distractor interference). Nevertheless, these data suggest a weakness in interference control in children with CI and further research is needed to clarify the nature of this problem. While comparison to language-matched peers or peers matched for duration of experience with device may provide valuable insight, this would have required our study to compare children with CI to much younger children. Future research could include a larger population of children with CI to permit the use of age as a predictor variable within mixed-model analyses to explore the role of auditory experience.

Although children with CI had lower accuracy in their offline comprehension of wh-questions when compared to their hearing peers, they did comprehend more than two-thirds of the questions. But eye gaze indicated much slower wh-question comprehension than their hearing peers, which may have been disproportionately affected by sentence length. These findings are consistent with previous findings throughout the pediatric CI literature; while many children with CI are capable of standardized language scores within normal limits, the impact of deprivation on discourse-level language development persists. The results highlight a need for targeted intervention on the production and comprehension of complex sentences like questions, and the consideration of working memory demands inherent in the length and complexity of these sentence types.

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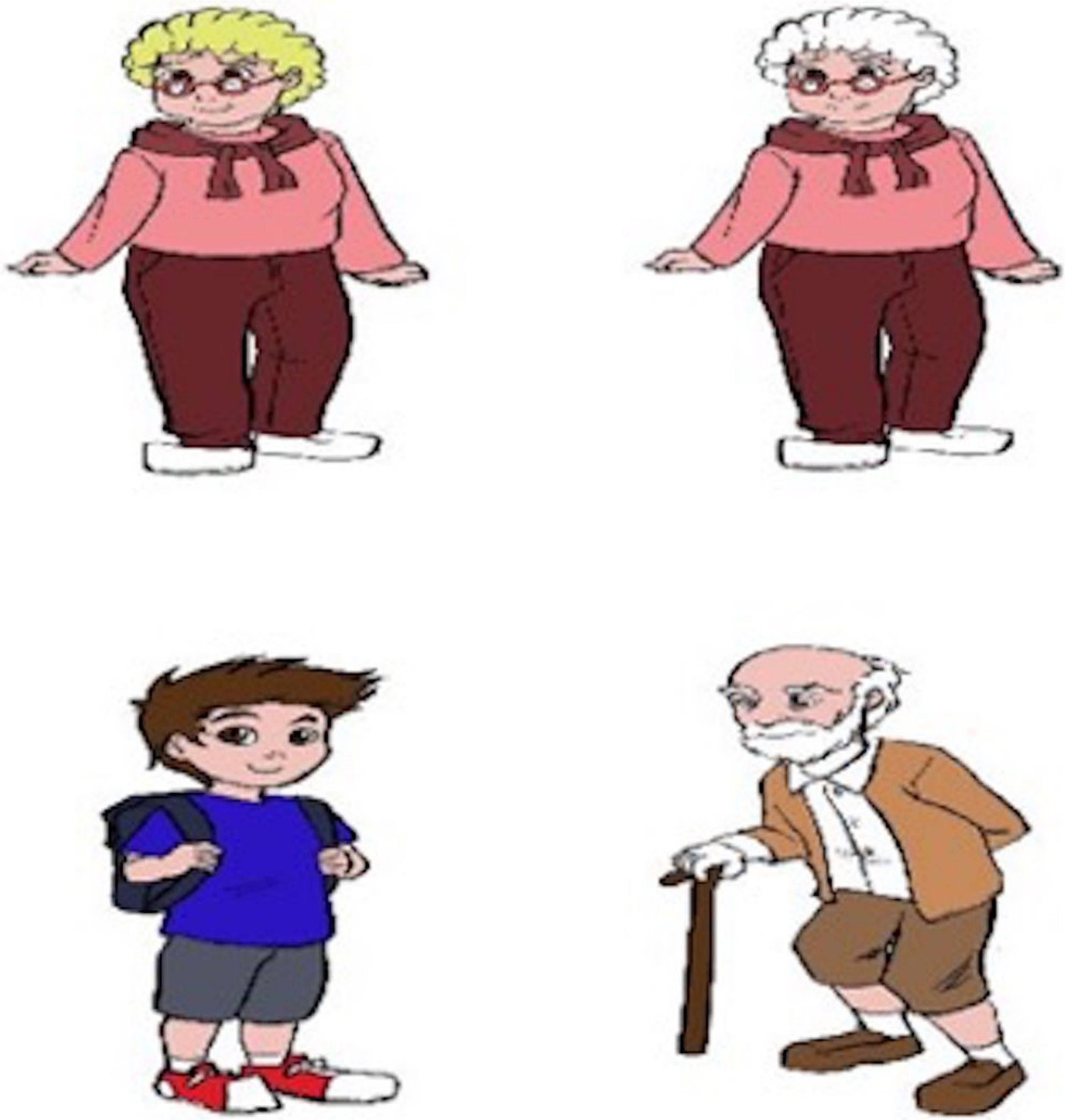

Figure 1.

Example of four picture array for the question “Who did the boy in the blue shirt kiss before school?” Paired with the context sentence, “The boy in the blue shirt kisses his grey-haired grandma before school”. Clockwise from top: the attribute foil of the object noun, the object noun, the noun foil of the object noun, and the subject noun.

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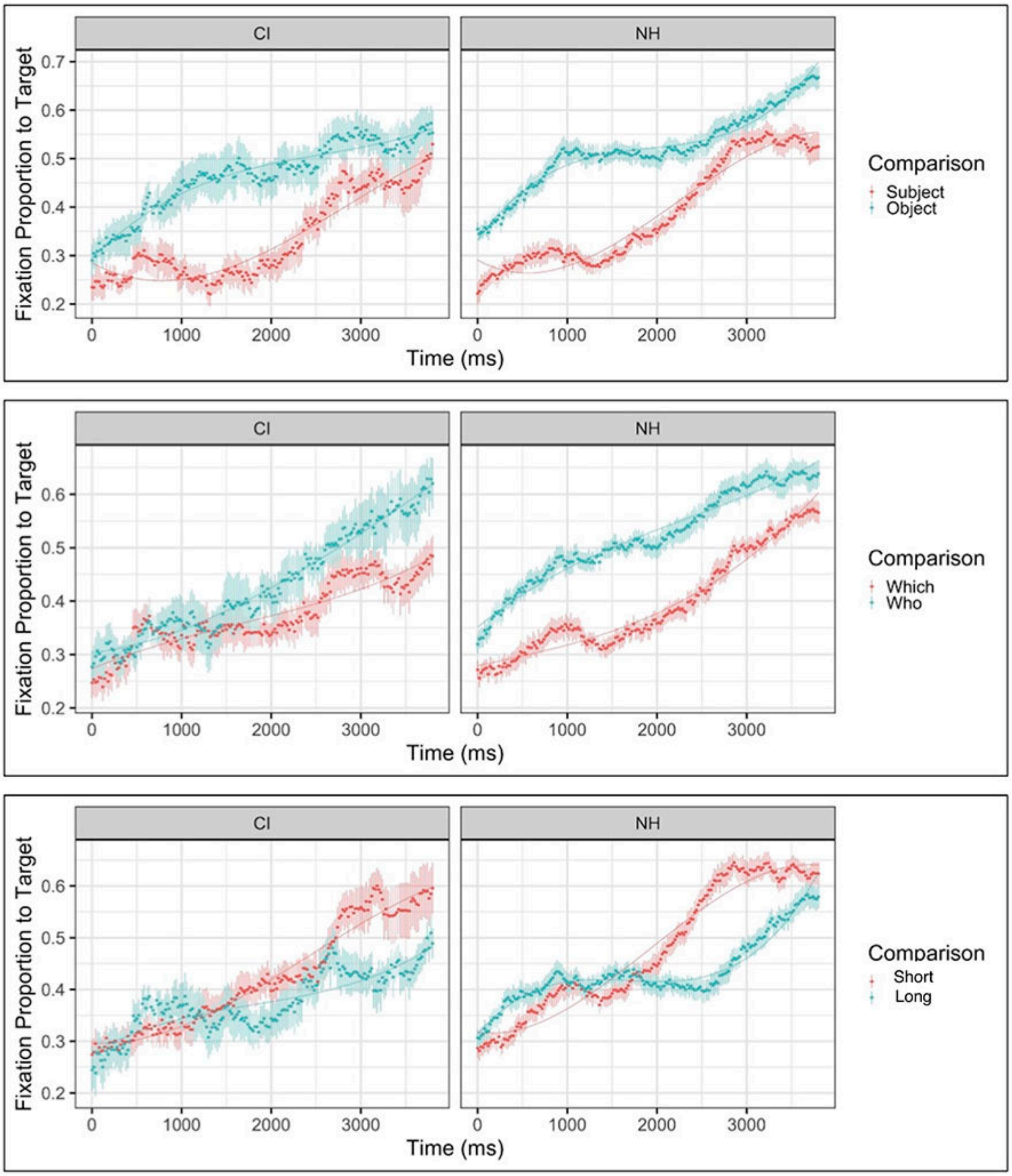

Figure 2.

Growth curve comparison of fixations to the target between children with CI and hearing children across question types (subject and object questions, which and who questions, and short and long questions.

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Table 1.

Demographic characteristics of participants

	Cochlear Implant (n = 16)		Hearing (n = 31)	
	M (SD)	**Range**	**M (SD)**	**Range**
Age (years)	9;10 (1;4)	7;11– 11;10	9;11 (1;5)	7; 4 – 11;11
Age at Implantation (years)	2;7 (1;8)	2;0 – 5;0		
Hearing Years at Testing	7;4 (1;8)	4;6 – 10;1		
Status (n)				
Bilateral CI	10			
Unilateral CI	1			
Bimodal (CI + Hearing Aid)	5			
Gender				
Male	9		13	
Female	7		18	
TONI-4	107.2 (11.7)	80-135	117.2 (10.7)	100-139
PPVT-4	96.9 (19.2)	64-129	116.6 (13.1)	95-141
CELF-4 (Core Language Score)	88.1 (21.7)	40-118	114.6 (11.8)	91-132

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Table 2.

Accuracy percentages by group and question type

	Cochlear Implant M (*SD*)	**Hearing M (*SD*)**
Question Target		
Object	67.6% (18.0)	83.8% (11.2)
Subject	70.2% (19.2)	83.7% (14.2)
Question Type		
Which	69.0% (13.4)	82.5% (13.7)
Who	67.6% (21.3)	85.2% (12.3)
Cognitive Load		
Short	72.1% (19.6)	85.7% (13.0)
Long	66.3% (16.6)	81.8% (12.3)
All Questions (80 questions presented)	68.8% (16.3)	83.8% (11.9)

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Table 3.

Results from Model One, which included fixed effects of comparison pairs by group (cochlear implant = 0/typical hearing = 1), question type (subject = 0/object = 1), question word (which = 0/who = 1), and question length (short = 0/long = 1) with random effects of participant and participant-by-pair.

Fixed Effects	B	SE	*p*	B	SE	*p*	B	SE	*p*	B	SE	*p*
	Group			QuestionType			QuestionWord			QuestionLength		
b_0	0.400	0.018	0.000	0.369	0.013	0.000	0.386	0.013	0.000	0.458	0.012	0.000
b_{Time}	1.023	0.098	0.000	1.285	0.088	0.000	1.065	0.082	0.000	1.525	0.076	0.000
b_{Time2}	0.093	0.084	0.265	0.278	0.072	0.000	0.210	0.073	0.004	0.063	0.074	0.397
b_{Time3}	−0.015	0.072	0.838	−0.194	0.064	0.002	0.051	0.056	0.359	−0.174	0.057	0.002
b_{Cmp}	0.056	0.023	**0.014**	0.132	0.012	**0.000**	0.104	0.012	**0.000**	−0.044	0.009	**0.000**
$b_{Time\ x\ Cmp}$	0.165	0.121	0.174	−0.308	0.113	**0.007**	0.134	0.105	0.202	−0.814	0.094	**0.000**
$b_{Time2\ x\ Cmp}$	0.013	0.103	0.899	−0.374	0.099	**0.000**	−0.203	0.102	**0.047**	0.095	0.104	0.362
$b_{Time3\ x\ Cmp}$	0.077	0.089	0.387	0.436	0.086	**0.000**	−0.016	0.077	0.836	0.439	0.075	**0.000**

*Significant *p* values are in bold. Each comparison (Cmp) corresponds to Group, QuestionType, QuestionWord, and QuestionLength.

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Table 4.

Results from Model Two, which included fixed effects of group (cochlear implant = 0/typical hearing = 1) and comparison pairs by question type (subject = 0/object = 1), question word (which = 0/who = 1), and question length (short = 0/long = 1) with random effects of participant and participant-by-pair.

Fixed Effects	B	SE	*p*	B	SE	*p*	B	SE	*p*
	QuestionType			**QuestionWord**			**QuestionLength**		
b_0	0.334	0.021	0.000	0.371	0.021	0.000	0.422	0.020	0.000
b_{Time}	1.064	0.149	0.000	0.760	0.135	0.000	1.355	0.129	0.000
b_{Time2}	0.376	0.122	0.002	0.040	0.123	0.746	0.159	0.127	0.209
b_{Time3}	−0.126	0.108	0.244	0.050	0.097	0.603	−0.098	0.096	0.311
b_{Cmp}	0.131	0.020	**0.000**	0.060	0.019	**0.002**	−0.046	0.015	**0.002**
b_{Group}	0.052	0.026	**0.045**	0.023	0.026	0.378	0.055	0.024	**0.025**
$b_{Time\ x\ Cmp}$	−0.155	0.195	0.428	0.545	0.179	**0.002**	−0.680	0.159	**0.000**
$b_{Time2\ x\ Cmp}$	−0.611	0.168	**0.000**	0.147	0.173	0.396	−0.132	0.177	0.455
$b_{Time3\ x\ Cmp}$	0.237	0.150	0.114	−0.078	0.133	0.561	0.199	0.122	0.103
$b_{Time\ x\ Group}$	0.335	0.184	0.068	0.464	0.166	0.005	0.257	0.159	0.105
$b_{Time2\ x\ Group}$	−0.148	0.151	0.328	0.258	0.151	0.087	−0.146	0.156	0.349
$b_{Time3\ x\ Group}$	−0.102	0.134	0.444	0.001	0.119	0.991	−0.115	0.119	0.332
$b_{Cmp\ x\ Group}$	0.002	0.025	0.948	0.067	0.024	**0.005**	0.004	0.018	0.835
$b_{Time\ x\ Cmp\ x\ Group}$	−0.232	0.241	0.335	−0.623	0.220	**0.005**	−0.204	0.196	0.300
$b_{Time2\ x\ Cmp\ x\ Group}$	0.360	0.207	0.081	−0.530	0.213	**0.013**	0.345	0.218	0.113
$b_{Time3\ x\ Cmp\ x\ Group}$	0.302	0.184	0.101	0.093	0.164	0.570	0.364	0.150	**0.016**

* Significant *p* values are in bold. Each comparison (Cmp) corresponds to QuestionType, QuestionWord, and QuestionLength.

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Table 5.

Results from Model Three included fixed effects of comparison pairs by question type (subject = 0/object = 1), question word (which = 0/who = 1), and question length (short = 0/long = 1) in children with typical hearing with random effects of participant and participant-by-pair.

Fixed Effects	B	SE	*p*	B	SE	*p*	B	SE	*p*
	QuestionType			QuestionWord			QuestionLength		
b_0	0.386	0.014	0.000	0.394	0.013	0.000	0.476	0.013	0.000
b_{Time}	1.399	0.105	0.000	1.223	0.084	0.000	1.612	0.082	0.000
b_{Time2}	0.228	0.076	0.003	0.298	0.078	0.000	0.013	0.074	0.858
b_{Time3}	−0.228	0.078	0.004	0.052	0.060	0.392	−0.213	0.063	0.001
b_{Cmp}	0.133	0.012	**0.000**	0.126	0.012	**0.000**	−0.042	0.010	**0.000**
$b_{Time \times Cmp}$	−0.387	0.142	**0.006**	−0.078	0.109	0.474	−0.883	0.098	**0.000**
$b_{Time2 \times Cmp}$	−0.251	0.102	**0.013**	−0.383	0.109	**0.000**	0.212	0.101	**0.036**
$b_{Time3 \times Cmp}$	0.539	0.103	**0.000**	0.016	0.074	0.832	0.563	0.075	**0.000**

*Significant *p* values are in bold. Each comparison (Cmp) corresponds to QuestionType, QuestionWord, and QuestionLength.

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Table 6.

Results from Model Four, which included fixed effects of comparison pairs by question type (subject = 0/object = 1), question word (which = 0/who = 1), and question length (short = 0/long = 1) in children with cochlear implants with random effects of participant and participant-by-pair.

Fixed Effects	B	SE	*p*	B	SE	*p*	B	SE	*p*
	QuestionType			QuestionWord			QuestionLength		
b_0	0.334	0.024	0.000	0.371	0.024	0.000	0.422	0.023	0.000
b_{Time}	1.064	0.154	0.000	0.760	0.166	0.000	1.355	0.154	0.000
b_{Time2}	0.376	0.151	0.013	0.040	0.146	0.786	0.159	0.164	0.331
b_{Time3}	−0.126	0.109	0.245	0.050	0.118	0.669	−0.098	0.113	0.386
b_{Cmp}	0.131	0.022	**0.000**	0.060	0.024	**0.014**	−0.046	0.017	**0.006**
$b_{Time\ x\ Cmp}$	−0.155	0.168	0.356	0.545	0.212	**0.010**	−0.680	0.185	**0.000**
$b_{Time2\ x\ Cmp}$	−0.611	0.199	**0.002**	0.147	0.192	0.444	−0.132	0.217	0.543
$b_{Time3\ x\ Cmp}$	0.237	0.143	0.097	−0.078	0.162	0.632	0.199	0.136	0.144

*Significant *p* values are in bold. Each comparison (Cmp) corresponds to QuestionType, QuestionWord, and QuestionLength.