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Sentence Recognition in Quiet and Noise by Pediatric Cochlear Implant Users: Relationships to Spoken Language

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INTRODUCTION

Cochlear implantation is the standard of care for children with severe to profound, sensorineural hearing loss. The success of this implantable auditory device can be attributed to the child's ability to process the acoustic-phonetic cues of speech during a sensitive period for auditory learning and spoken language development. In the United States, children are implanted as early as 12 months of age, and even younger. It is evident from the literature that the earlier the age at implantation, the greater the likelihood that the child will attain spoken language skills similar to children with normal hearing (1–3). Despite impressive outcomes, however, variability in communication skills remains characteristic of the pediatric CI population (3,4). Such factors as age at implantation, socio-economic status, maternal sensitivity to communication needs, and aided residual hearing, among others, partially explain the variance in language competency.

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Implicit in these outcomes is the understanding that the CI does not restore hearing to normal perceptual levels. That is, the processed speech signal is degraded even when the CI recipient is listening under optimal conditions and is able to detect sound across the frequency range for speech. Although today's commercial devices differ in the number of electrodes and signal processing options, CI users are able to recognize speech presented in quiet with between four to eight electrodes (5–7), configured to represent an equivalent number of spectral channels. Impressively, four spectral channels appear adequate for adults with normal hearing to recognize speech when listening through a noise-band vocoder that simulates continuous interleaved sampling (CIS) (8), a CI processing strategy.

Using this same noise-band vocoder, Eisenberg et al (9) conducted a study with 2 groups of children (ages 5–7 and 10–12 years) and 1 group of adults, all with normal hearing, to investigate the developmental time course of speech recognition with reduced spectral cues as represented by the CIS vocoder simulation. Results indicated that children in the youngest age group (5 to 7 years) required a greater number of spectral channels to achieve scores equivalent to older children and adults on speech feature contrasts, words and sentences. The discrepancy was most notable for the sentence recognition test, underscoring the reliance on linguistic knowledge.

To better understand these findings, j-factor analysis (10,11) was performed to parse out the “parts to whole” context effects influencing phoneme, word, and sentence recognition. With respect to sentence recognition, the j-factor analysis indicated that the youngest age group was not as successful as the older age groups in using sentence context to recognize the words within sentences.

To further explore why some children with CIs aren't taking advantage of context in sentence recognition, the role of syntactic context on word and sentence recognition was investigated in children with CIs (12) and children with normal hearing listening under CIS simulation (12,13). The results indicated that children's inability to utilize syntactic context is exacerbated by deficits in vocabulary knowledge (12,13), verbal short-term memory, and/or cognitive control processes (13).

In addition to potential difficulties in utilizing context, speech recognition scores of CI users are further degraded by background noise. In Friesen et al (7), adults with CIs required as many as 10 spectral channels to recognize words and sentences in noise, indicating that more fine-grained spectral resolution is needed for separating the speech from the noise. With pediatric CI users, a number of studies have demonstrated the interfering effects of noise and other competing signals (14–18). Thus, children with CIs are disadvantaged by a combination of reduced numbers of spectral channels, noise interference, and context effects.

Word and sentence recognition capabilities are formative to emerging spoken language skills. For children with CIs, significant associations have been reported between language and speech perception scores, specifically for speech pattern contrast perception (19), and for word and sentence recognition in quiet (12,20). To our knowledge, similar relationships have not been explored for speech that is presented in noise. Classrooms are often noisy and

not optimal for general auditory learning; background noise poses distinct disadvantages for language learning, even among children with normal hearing (21,22). The effects of background noise on the pediatric CI user can be expected to further hinder learning. Although FM systems can substantially improve the S/N in the classroom (18), such devices are not used consistently across all listening conditions and environments.

In the present study, associations between sentence-recognition scores from the Hearing In Noise Test for Children (HINT-C) (23) and standard scores from the Comprehensive Assessment of Spoken Language (CASL) (24) were examined across 3 test intervals for children participating in the Childhood Development after Cochlear Implant (CDaCI) study (3,4,25). Analysis of CASL scores by discrete HINT-C word-score categories provided a window to emerging sentence recognition in noise at 48-, 60-, and 72-month post CI activation.

MATERIALS AND METHODS

Participants

The CDaCI study is an ongoing prospective, longitudinal study that commenced in 2002. The extensive assessment protocol tracks children annually on spoken language, speech recognition, psychosocial functioning, and quality of life. A comprehensive description of the CDaCI study with complete subject demographics has been described by Fink et al. (25). Enrolled under the age of 5 years are 188 children with severe to profound hearing loss from 6 CI centers and 97 normal-hearing controls from 2 centers. In the present study, the number of CI participants varied across test intervals and listening conditions due to criterial requirements for HINT-C test administration. Table 1 shows the number and mean age (range) of CI participants assessed at each of 3 test intervals (48, 60, and 72 months) and at each of 4 HINT-C listening conditions (quiet, +10, +5, 0 dB signal-to-noise ratio [S/N]) as well as other descriptive information relevant to the study.

Sentence Recognition

HINT-C sentences were administered in quiet and in speech-shaped noise within the context of the hierarchical speech recognition test battery assembled for the CDaCI study (17). The test instruments that constitute the CDaCI hierarchy were selected to assess an array of age- and developmentally appropriate auditory skills progressing from rudimentary sound awareness through open-set speech recognition. To advance through the battery, a child was required to demonstrate a criterion level of performance on an earlier, easier test before moving on to the next more difficult test. Once a child demonstrated ceiling performance on a given instrument over 2 consecutive follow-up intervals, testing with that instrument was discontinued. Thus, the number of children assessed using a specific instrument changes across test intervals, as children move through the CDaCI test hierarchy.

Within the hierarchical battery, HINT-C sentences were introduced once the child reached 5 years of age and demonstrated >0% performance in open-set word recognition (Phonetically Balanced Kindergarten Word Lists, PBKs) (26). Recorded HINT-C sentences were delivered via loudspeaker (0° azimuth) at a presentation level of 70 dBA. Sentences were

scored for both words correct and sentences correct, over a total 20 sentences per condition. Testing in noise (+10 dB S/N) was introduced once the child achieved a HINT-C word score of 20% in the quiet condition. S/Ns of +5 and 0 dB were added as the child achieved words scores of 20% correct at +10 and +5 dB S/N, respectively.

Language

Language testing under the CDaCI protocol followed age determined criteria. That is, in the early years of enrollment, children were administered language tests to assess prelinguistic and early linguistic skill development. With increasing age and the expectation for symbolic language use, the CASL was introduced at 48 months post CI.

The CASL was developed to assess a range of receptive and expressive language abilities for normal hearing children, ages 3 years, 0 months, 21 years, 11 months. It is comprised of 15 tests that are reflective of four structural knowledge categories (Lexical/Semantic, Syntactic, Supralinguistic, and Pragmatic). The CASL was designed such that the specific tests administered at any point in time are intended to assess skills that typically developing children are expected to achieve at a given chronological age. A core composite of tests consisting of 4 or 5 measures is typically recommended, dependent upon the child's age band (e.g., 5–6 years, 7–10 years, 11–12 years, etc.). Thus, the core test battery changes as children grow older. Regardless of age, the tests that make up the core composite are intended to capture skills underlying each of the four knowledge categories.

Raw scores were converted to standard scores, based on performance of typically developing children of the same age. Whereas raw scores were expected to increase over time as the children's language skills improve, standard scores tend to remain flat unless a child shows a substantially faster or slower rate of developmental changes compared to the normative group. A standard score for the overall core composite was obtained across the tests administered at a given interval. In addition to core composite, standard scores were analyzed for the following tests: antonyms (word retrieval and knowledge), syntax construction (expression of phrases and sentences), paragraph construction (comprehension of syntactic structures), and pragmatic judgment (knowledge and use of language).

For the present analysis, children were administered the core battery of tests for their age at 48, 60, and 72 months post CI activation. At the 48 month test point, children ranged in age from 56 months up to 112 months and at the 72 month test point children were between 80 months and 139 months of age.

Statistical Methods

The CDaCI hierarchical speech recognition battery provides information about children's skill levels, even in the absence of an actual test score. Speech recognition was assessed only after the child was considered developmentally ready for the HINT-C. Within the 4 HINT-C test conditions, a similar hierarchy was followed, in which a more difficult test condition was administered if the child met criterion at the easier condition. For example, the HINT-C +10 dB S/N would be administered only if the child met criterion in quiet (per protocol, > 20% words correct). Each HINT-C test condition was scored by percentage words and sentences correct.

Children's HINT-C word scores were first categorized on a 5-point continuum of speech recognition skill development across the 3 evaluations, ranging from "not ready for the HINT-C" to "acquired speech recognition in noise skill" (see Figure 1 and Table 1). Performance on HINT-C at +10 and +5 dB S/N conditions were used to create the categories. With the exception of the first category ("not ready"), assignment of skill level was based on the words correct (greater than 50% versus less than 50%) for the combination of the +10 and +5 S/N conditions. The variable "age at implant" was divided into two categories: < 2.5 years of age and 2.5 years and older, in accordance with Tobey et al. (4).

The analyses proceeded in two steps. First, the CASL composite standard scores were examined across the 3 evaluations using repeated measures modeling in SPSS 22.0. The Fixed factors were HINT-C Skill Level category (defined in Figure 1), Implant Age category, and Test Interval. All data from the CI study sample were included in the analysis of the effects of HINT-C Skill level on CASL composite scores. If the CASL composite standard score did not differ by HINT-C Skill Level, then speech recognition in noise skill was not associated with spoken language ability. If the CASL composite scores did differ by HINT-C Skill Level, then speech recognition in noise skill would inform clinical understanding of spoken language skills in children with a CI. Second, the portion of the CI sample with HINT-C sentence scores available at each evaluation were further examined for associations with CASL test scores. The associations provide an examination of which spoken language abilities may or may not be associated with speech recognition in noise performance during the developmental interval when the child is likely to acquire those skills. Alpha was set at <0.05 indicating statistical significance.

RESULTS

Effect of HINT-C Skill Level on CASL Composite Standard Score

Note in Table 1 that the preponderance of the sample was "not ready" (i.e., did not yet meet criteria) for HINT-C testing at 48 months (45%) and therefore was "missing" HINT-C scores. By 72 months, 52% of the sample had achieved >50% words correct in both the +10 and +5 S/N conditions.

Figure 2 shows the average CASL composite standard score by evaluation interval and HINT-C Skill Level. A repeated measures model analysis was carried out on the CASL composite standard score, with Evaluation as the repeated factor (the residuals were modeled using an autoregressive structure). Fixed effects of HINT-C Skill Level, Evaluation, and Implant Age, and all 2-way interactions were entered into the model. The complete model accounted for 60% of the variance observed under the null model (27). The main effect of HINT-C Skill Level ($F(4,164.7)=49.9$, $p<.0001$) was significant, as was the interaction of HINT-C Skill with Evaluation ($F(8, 264.4)=5.1$, $p<.0001$). As in Tobey et al (4), a main effect of Implant Age was verified. Those children implanted at 30 months of age or younger yielded a significantly higher CASL composite standard score ($M=77$) relative to those implanted over the age of 30 months ($M=66$) ($F(1,154.8)=20.3$, $p<.0001$).

Decomposition of the HINT-C Skill and Evaluation interaction was carried out using Evaluation as a repeated measures factor at each level of HINT-C skill and the Bonferroni

correction for multiple comparisons. Univariate analyses revealed that the 2 lowest HINT-C Skill categories (“not ready”, “<50%”) showed a significant decrease in average CASL composite score between the 48-month and 60-month evaluation. In contrast, the 2 highest HINT-C Skill groups (“>50%”, “always 50%”) showed significant increases in average CASL composite scores across evaluation. No other effects were statistically significant.

Associations between HINT-C sentence scores and CASL standard scores

Figure 3 shows the association of HINT-C sentence percent correct with the CASL composite standard score across HINT-C test condition and Evaluation. The subjects in these analyses are a subset of the entire sample (see Table 1), as the HINT-C became developmentally appropriate and they were able to achieve some level of performance, even if very low, as in the HINT-C 0 dB S/N condition. Overall, the better the HINT-C performance, the better the CASL composite score in quiet, +10, and +5 dB S/N. This relationship was much less evident at 0 dB S/N, likely due to the inability of most subjects to obtain greater than 10% sentences correct.

Table 2 displays Kendall’s tau among the CASL tests and HINT-C sentence scores for condition and test interval. The results demonstrated statistically significant associations for most of the CASL tests with HINT-C scores in quiet, +10, and +5 dB S/N. All significant taus were positive, indicating that better HINT-C scores are associated with higher CASL test standard scores. At 48 months, the strongest relationship across 3 HINT-C test conditions was for the antonym subtest. This result suggests that word-specific information plays an important role in spoken language acquisition. At 60 months, the strongest association was observed between HINT-C quiet and +10 dB S/N and the syntax construction (expressive) test. At +5 dB S/N, however, the strongest relationship was with paragraph comprehension, a test of the receptive aspects of syntax. At 72 months, the strongest associations were with both syntactic tests (syntax construction and paragraph comprehension). At this test interval, performance in the +10 dB S/N condition had a slightly stronger association with paragraph comprehension performance. There would appear to be a developmental effect, in that the shared variance between HINT-C tests and CASL tests shifts over time from a lexical construct to a syntactic construct. In contrast, most of the relationships did not reach statistical significance at 0 dB S/N, due to small numbers of subjects who could be administered the test and the difficulty of that condition for CI children.

DISCUSSION AND CONCLUSION

One of the objectives of the CDaCI study is to track speech recognition and language in parallel and in relation to each other. In the present study, we explored the speech recognition/spoken language relationship for children with CIs in the early school-age years when speech recognition and language structures are increasing in complexity. The speech recognition hierarchy was compiled so that each child could progress through successively more difficult tests at his or her own pace. Attaining the highest level of difficulty—sentence recognition in noise—represents advancement through measures that encompass pattern perception, closed-set word and sentence identification in quiet and competition, and open-set word and sentence recognition in quiet. By the time the child reaches sentence

recognition in noise, he or she is at least 5 years of age and likely using complex oral language constructions.

Because of the demands of the speech recognition hierarchy, those children reaching sentence recognition assessment in noise by 48-, 60-, and 72 months post CI activation represented a subset of children in the CDaCI study who demonstrated the most rapid advancement through the hierarchy. In contrast, all of the CDaCI participants were administered the CASL commencing at the 48-month test interval (4). Figure 2 categorizes the CASL composite scores for the entire sample by the five HINT-C word-score skill levels described in Figure 1. Notably, those children not ready to be assessed on the HINT-C test fell into the first category. In general those participants with HINT-C word scores less than 50%, including those not yet assessed on the HINT-C, demonstrated lower CASL composite scores than the rest of the sample and further showed significant decrements in CASL composite scores over the 3 test intervals. In contrast, HINT-C word scores of 50% or greater reflected improvements in CASL scores over time.

The data from those children tested with both the HINT-C and CASL at all 3 test intervals were submitted to Kendall's analyses using HINT-C sentence scores. The scatter plots in Figure 3 showed linear relationships between sentence recognition scores (quiet and +10 dB S/N) and CASL core composite scores across the 3 test intervals. As the listening condition became more challenging (+5 dB S/N), the relationships began to break down; at 0 dB S/N, linearity was negligible. Such results are not surprising, particularly at 0 dB S/N (14), because CI processors don't provide the fine-grained spectral detail that would be required to recognize speech under the most challenging noise levels (7). Impressively, the children with high levels of language, as evidenced by the CASL standard scores, attained these skills despite listening through reduced numbers of spectral channels and inconsistent listening environments.

Positive Kendall's coefficients, shown in Table 2, were statistically significant among sentence recognition scores (primarily in quiet, +10, and +5 dB S/N) and most of the CASL tests evaluated (antonyms, syntax construction, paragraph comprehension, and pragmatic judgment). At the 48-month interval, the strongest associations found were between sentence recognition and CASL antonym standard scores, representing word retrieval and knowledge of opposites. Data by Caldwell and Nittrouer (14) for monosyllabic words showed similar findings in that scores on tests of auditory comprehension and expressive vocabulary explained a significant amount of variance for word recognition in noise in children with hearing aids and CIs. Eisenberg et al. (12) reported that children with CIs who had high receptive vocabulary scores also were able to recognize words more accurately in sentences as opposed to words in isolation. The opposite pattern was shown for children with low vocabulary scores. Moreover, low sentence recognition scores were associated with poor language scores in the Conway et al study (13). Taken together the present results support the notion that the children with lower sentence-correct scores may not be processing sentences as a whole but, rather, as individual words.

At the 60- and 72-month test intervals, the 2 CASL syntax tests (syntactic constructions and paragraph comprehension) yielded the strongest associations with sentence recognition.

Thus, those children with the highest scores for both sentence recognition and language may, in fact, have developed the skill set necessary to recognize entire sentences with support of syntactic knowledge by 5 to 6 years post CI activation.

Fortunately, many school-age children with CIs receive assistance in the classroom with FM systems, shown to improve sentence-in-noise thresholds by up to 20 dB (18). Depending on the FM system arrangement, however, children with CIs may have difficulty during general classroom discussions or in interacting with classmates during recess or lunchtime. As children with CIs advance through their educational programs, demands on communication skills may become more of a barrier to academic achievement due to varying levels of background noise. It is hoped that future developments in technology, noise reduction algorithms, assistive technology, and improvements in classroom acoustics will facilitate communication skill development for pediatric CI recipients.

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Figure 1.

Categorization of performance based on HINT-C word recognition over time. The left column indicates whether or not the HINT-C was administered, and if so, the categorization based on perception words correct (<50% or >50%) for both the +10 and +5 dB S/N conditions. The right column indicates the skill level associated with the HINT-C performance.

Figure 2. Average CASL composite standard score by HINT-C skill level category and evaluation. The brackets and asterisks indicate significant differences within the HINT-C skill level category across evaluation.

Figure 3.

Scatterplot of HINT-C sentence percent correct by HINT-C test condition, CASL composite score, and evaluation. Correlation coefficients with an asterisk are statistically significant.

Table 1

CI participants' demographics and skill level by test interval.

		48 Month	60 Month	72 Month
	n	150	155	142
Age at test	Mean	6.5	7.4	8.5
	SD	1.2	1.2	1.2
Female	%	55	54	58
Additional Disabilities	%	15	17	17
Normal inner ear imaging	%	79	74	73
Implant < 30M	%	57	59	59
At least some college education (mother)	%	81	82	82
Nonwhite	%	33	34	32
HINT-C Condition Sample Size				
Quiet	n	103	107	75
@+ 10 dB S/N	n	83	94	77
@+ 5 dB S/N	n	61	69	69
@0 dB S/N	n	35	45	35
HINT-C Skill Level at Each Evaluation				
Not ready	%	45	25	14
<50% @+10/+5 dB S/N	%	10	12	6
< 50% @+10/+5 dB S/N	%	9	14	13
>50% @+10, <50% @+5 dB S/N	%	11	11	15
>50% +10/+5 dB S/N	%	25	39	52

Table 2

Kendall's tau between HINT-C categories of performance (Figure 2) and CASL test scores by test interval.

48 Month	Antonym	Syntax	Paragraph Comprehension	Pragmatic Judgment
Quiet	0.55 *	0.53*	0.49*	0.50*
@+10 dB S/N	0.52 *	0.39*	0.39*	0.34*
@+5 dB S/N	0.38 *	0.23*	0.33*	0.24*
@0 dB S/N	0.05	−0.05	−0.22	−0.13
60 Month	Antonym	Syntax	Paragraph Comprehension	Pragmatic Judgment
Quiet	0.54*	0.58 *	0.57*	0.57*
@+10 dB S/N	0.49*	0.55 *	0.53*	0.53*
@+5 dB S/N	0.34*	0.39*	0.42 *	0.36*
@0 dB S/N	0.22	0.27*	0.20	0.29 *
72 Month	Antonym	Syntax	Paragraph Comprehension	Pragmatic Judgment
Quiet	0.58*	0.69 *	0.66*	0.63*
@+10 dB S/N	0.39*	0.54*	0.55 *	0.45*
@+5 dB S/N	0.24*	0.33*	0.34 *	0.29*
@0 dB S/N	−0.03	−0.08	−0.07	−0.12

* =p<.05, **bold** indicates highest tau with HINT-C Condition