

Speech Recognition at 1-Year Follow-Up in the Childhood Development after Cochlear Implantation Study: Methods and Preliminary Findings

Laurie S. Eisenberg^a Karen C. Johnson^a Amy S. Martinez^a
Carol G. Cokely^b Emily A. Tobey^b Alexandra L. Quittner^c Nancy E. Fink^d
Nae-Yuh Wang^d John K. Niparko^d and the CDaCI Investigative Team¹

^aHouse Ear Institute, Los Angeles, Calif., ^bCallier Center for Communication Disorders, University of Texas at Dallas, Dallas, Tex., ^cDepartment of Psychology, University of Miami, Miami, Fla., ^dJohns Hopkins University, Baltimore, Md., USA

Key Words

Cochlear implants · Severe to profound hearing loss · Speech recognition

Abstract

The Childhood Development after Cochlear Implantation (CDaCI) study is a longitudinal multicenter investigation designed to identify factors influencing spoken language in young deaf children with cochlear implants. Normal-hearing peers serve as controls. As part of a comprehensive evaluation battery, a speech recognition hierarchy was designed to assess how well these children recognize speech stimuli across developmental stages. Data were analyzed for the earliest measures in 42 pairs of children reaching 1 year of follow-up. A number of children in the cochlear implant group who met criteria for testing approached levels of performance similar to the normal-hearing controls, and some could identify sentences in competition. These results demonstrate the re-

sponsiveness of the speech recognition hierarchy in tracking emergent skills from a sample of the CDaCI cohort.

Copyright © 2006 S. Karger AG, Basel

Introduction

Over the past 3 decades, cochlear implantation has become the treatment of choice for individuals with severe to profound hearing loss who derive minimal benefit from conventional amplification. The cochlear implant (CI) is a surgically implanted sensory device that converts incoming sounds to electrical impulses, which are then bandpass filtered and delivered to select electrodes situated along the scala tympani of the cochlea. Implanted electrodes deliver electrical impulses to discrete tonotopic regions of the cochlea, bypassing impaired hair cell transducers and directly stimulating residual auditory neural elements. A transmitter, signal processor and microphone are worn externally to transmit encoded signals to the CI. One of the most direct ways to determine benefit with a CI is by demonstrating improvements in speech

¹ For members of the CDaCI Investigative Team, Resource Centers and Study Oversight Committees, see appendix.

recognition. Present results indicate that postlingually deafened adults achieve moderate to high levels of speech recognition with multichannel implant systems [Kirk, 2000], which is substantially better than performance levels attained with well-fitted hearing aids.

Cochlear implantation of children was initiated in the United States in 1980 when a 10-year-old, congenitally deaf child was implanted with a single-channel device [Eisenberg et al., 1983]. The average age at time of surgery in the first pediatric clinical trials was approximately 8 years, and more than half of those children communicated by sign language [Berliner et al., 1985]. With performance levels steadily improving as a result of more technologically advanced multichannel implant systems [e.g., Franz, 2002; Osberger and Koch, 1991; Osberger et al., 2002; Staller, 1991; Staller et al., 2002], coupled with earlier identification of hearing loss, prelingually deafened children today have greater opportunities than they did in earlier years to acquire spoken language and be mainstreamed into regular educational settings. In fact, children are now being implanted as young as 1 year of age (in accordance with FDA guidelines) and, in some cases, even younger [Colletti et al., 2005; James and Papsin, 2004; Waltzman and Roland, 2005]. As a point of reference, children with CIs have recently been compared to hearing aid users with moderate to severe hearing loss [Boothroyd and Boothroyd-Turner, 2002; Eisenberg et al., 2004].

Although CI efficacy is still weighted heavily against performance with conventional amplification, the field has evolved such that communication outcomes and rate of improvement by children with CIs are now referenced to normal-hearing (NH) peers. A multicenter longitudinal cohort study titled Childhood Development after Cochlear Implantation (CDaCI) was designed to make this comparison by incorporating a NH control group. Using a global view of childhood outcomes, the national CDaCI study aims to identify factors that impact spoken language, speech recognition, cognitive, behavioral, and psychosocial performance in young children with CIs compared to young children with normal hearing. The cohort includes 188 children with implants (CI group) and 97 NH children (NH group) enrolled between 2002 and 2004. Children are assessed at baseline (prior to implant surgery for the CI group) and at 6-month follow-up intervals for 3 years.

Evaluation of speech recognition remains essential in defining outcomes in the CDaCI investigation. The ability to recognize speech represents an integration of sensory, linguistic, and cognitive processes that involve

acoustic-phonetic identification and lexical access from long-term memory. When the sensory input is degraded, as in sensorineural hearing loss, the ability to make the fine acoustic-phonetic distinctions is compromised. Speech recognition is age-dependent and constrained by vocabulary knowledge, phonemic categorization, language competency and decision-making abilities [Boothroyd, 1970; Kirk et al., 1997].

Assessment of speech recognition in children with CIs poses methodological challenges that are common to studies of developmental learning. Formal assessments often mandate a structured clinical setting that is not necessarily conducive to eliciting a child's best cooperative effort [Kirk, 2000]. Investigators therefore must rely on a battery of engaging, age-appropriate measures most likely to yield data that are free of ceiling and floor effects in longitudinal assessment. A major challenge in the CDaCI study has been to identify developmentally appropriate measures of speech recognition for CI and NH cohorts that reflect an extremely wide range of perceptual capabilities throughout development in early childhood. This is particularly relevant for the age group of interest in the present study (<5 years), as it coincides with a phase of rapid acquisition of auditory milestones. In response to this challenge, a hierarchical approach has been formulated that combines measures of auditory perceptual ability to assess communicative behaviors for children from toddler to kindergarten stages.

We contend that rate of development between and within measures, along with other predictive factors, is important and may help to explain variation in speech recognition outcomes following cochlear implantation. The hierarchical approach is designed to address the question of whether cochlear implantation facilitates development of speech perception in ways that parallel this development in normally hearing children. The purpose of this report is to describe the speech recognition hierarchy and to analyze results on the first group of children completing the 1st year of follow-up in the CDaCI investigation.

Methods

Participants

Eligibility criteria included age younger than 5 years, achievement of age-specific developmental criteria (Bayley >70 for children less than 2 years; Leiter-R >66 for children 2 years or older) and a commitment that the child would be educated in the English language. Participants were 42 children with multichannel CIs (mean age = 2.3 years) and 42 NH controls (mean age = 2.7 years)

who had all reached 1-year follow-up. Data were obtained from six collaborating sites: House Ear Institute, Johns Hopkins University, University of Miami, University of Michigan, University of North Carolina, and University of Texas at Dallas. Demographic information is detailed in table 1, including gender, age at identification of hearing loss, age at baseline, hearing level, communication mode, and parent's education. The Institutional Review Boards of each participating center approved the study protocol. Written informed consent was obtained from each participating family.

Speech Recognition Hierarchy

We developed a speech recognition hierarchy structured according to the child's age and functional hearing ability. Preschool and school-age batteries that comprise the speech recognition hierarchy incorporate measures that assess pattern perception as well as word and sentence recognition presented in open and closed sets (table 2). Closed-set tasks are those in which a limited number of potential choices are available to the listener. In contrast, open-set tasks use no predefined response alternatives; the number of choices is unlimited. Parent questionnaires and criteria-referenced rating scales assess the child's meaningful use of sound with sensory devices in their home environments and everyday listening situations.

The speech recognition hierarchy evolved from earlier pediatric investigations conducted by the Central Institute for the Deaf (CID) [Geers, 1994] and Indiana University School of Medicine (IU) [Kirk, 2000]. The CID test battery was hierarchical, commencing with detection and progressing to auditory-visual then auditory-only, open-set word recognition measures. In contrast, the IU investigative team assembled separate batteries for preschool- and school-age children; all tests within the specified battery were attempted. In developing the CDaCI assessment batteries, the hierarchical approach was adopted from the CID protocol and the age-based approach was implemented from the IU protocol.

For each measure of the CDaCI hierarchy, a criterion level of performance is required before proceeding to the next level of difficulty, as outlined in table 2. Testing is discontinued on a specific measure once ceiling is reached on two consecutive test intervals. A consequence of this progression is that fewer numbers of children are assessed on the more difficult tests, particularly at this stage of the investigation. Due to the fact that only a small number of children have reached school age at this stage of the investigation, the data reported herein are for the earliest tests within the Preschool Battery, which consist of the Infant-Toddler Meaningful Auditory Integration Scale (IT-MAIS) [Zimmerman-Phillips et al., 2000], Meaningful Auditory Integration Scale (MAIS) [Robbins et al., 1991], Early Speech Perception Test (ESP) [Moog and Geers, 1990], and the Pediatric Speech Intelligibility Test (PSI) [Jerger and Jerger, 1984].

The MAIS probes ten questions in a structured parent interview, assessing the child's bonding with the sensory device, auditory awareness, and ability to derive meaning from sound in everyday situations. For each probe, the parent responds using a scale (0–4) to indicate how often the child engages in the auditory behavior being explored. The IT-MAIS shares the majority of the ten probes with the MAIS, but differs on questions that specifically explore the vocal behavior of infants with their sensory device. For the NH controls, the two items relating to device bonding (MAIS) and the one item relating to vocal behavior with the device (IT-MAIS) have been eliminated. These changes result in maximum

Table 1. Demographic summary of CDaCI participants

	NH controls (n = 42)	CI group (n = 42)
Gender		
Male	22 (52%)	18 (43%)
Female	20 (48%)	24 (57%)
Age at identification of hearing loss, mean years (SD)	N/A	1.0 (1.0)
Age at baseline, mean years (SD)	2.7 (1.1)	2.3 (1.3)
Average hearing level (0.5, 1, 2, 4 kHz)		
Right ear mean dB HL (SD)	12.3 (5.1)	111.7 (15.9)
Left ear mean dB HL (SD)	11.7 (5.8)	115.7 (17.1)
Communication mode at baseline		
Oral ¹	42 (100%)	13 (31%)
Total communication ²	0 (0%)	25 (59.5%)
Undecided ³		4 (9.5%)
Parent's education		
<High school	0 (0%)	3 (7%)
High school graduate	2 (5%)	6 (14%)
Some college	2 (5%)	8 (19%)
College graduate	38 (90%)	24 (57%)
No response	0 (0%)	1 (2%)

¹ Auditory verbal, aural/oral, cued speech, or any combination of these methods.

² Sign (manual) language and/or fingerspelling with or without an accompanying oral (spoken) component.

³ Undetermined, children <1 year of age.

scores of 32 for the MAIS and 36 for the IT-MAIS in contrast to the maximum score of 40 for the CI group. Thus, for comparison purposes, total scores are converted to percentages, representing the quotient of the achieved score as observed by the parent divided by the maximum that is achievable. The IT-MAIS and MAIS are administered to parents of children below and equal to or above the age of 4 years, respectively.

The ESP is generally introduced when the child is 2 years of age or when he or she is able to choose between two alternatives. The ESP is designed to assess pattern perception (differentiation of syllable number and stress pattern), spondaic word identification (two syllable words with equal stress on each syllable), and monosyllabic word identification in a closed set. Attainment of a criterion level is required to pass each subtest. Performance is classified into one of four categories, representing increasing levels of auditory skill: detection (category 1), pattern perception (category 2), some word identification (category 3), and consistent word identification (category 4). For efficiency, testing is initiated at the most difficult subtest for the NH controls, regressing to easier levels as needed. Two versions of the ESP are used to accommodate the range of ages and linguistic abilities of children in the sample. The standard version of this test uses picture plates of 12 items, each to depict syllabic patterns and word targets known by most hearing-impaired children by the age of 6 years. The low-verbal version uses objects

Table 2. CDaCI speech recognition hierarchy: preschool and school-age batteries

Test	Stimulus	Age and performance criteria	Response format
<i>Preschool battery</i>			
IT-MAIS [Zimmerman-Phillips et al., 2000]	10 probes ¹	1–3 years	parent report
MAIS [Robbins et al., 1997]	10 probes ¹	4 years +	parent report
ESP – low verbal [Moog and Geers, 1990]	spondaic and monosyllabic words	2 years +; able to select between two alternatives	closed set
ESP – standard version [Moog and Geers, 1990]	spondaic and monosyllabic words	3 years +; able to select between two alternatives	closed set
PSI [Jerger and Jerger, 1984]	words and sentences in quiet and competition	3 years +; category 3 or 4 on ESP	closed set
Multisyllabic Lexical Neighborhood Test [Kirk et al., 1995]	multisyllabic words	3 years +; PSI > 20%	open set
Lexical Neighborhood Test [Kirk et al., 1997]	monosyllabic words	3 years +; PSI > 20%	open set
<i>School-age battery</i> ²			
Phonetically Balanced Word Lists – Kindergarten [Haskins, 1949]	monosyllabic words	5 years +; scores > 0% on LNT	open set
Hearing in Noise Test – Children [Gelnett et al., 1995]	sentences in quiet and noise	5 years +; scores > 0% on LNT	open set

¹ Nine probes for the NH controls.

² Tests from preschool battery overlap with school-age battery.

and a smaller response set than the standard version, and is appropriate for children in the 2- to 3-year age range or those with limited vocabularies. Stimuli for both versions are typically presented with live voice.

The PSI is introduced when the child is 3 years of age and/or when category 3 or 4 on the ESP is achieved. The PSI assesses the child's ability to identify words and sentences depicted on a picture plate from a closed set of five alternatives. The digitally recorded PSI stimuli [Eisenberg and Dirks, 1995] are delivered via loudspeaker situated directly in front of the child (0° azimuth). The same talker is used both for target and competing stimuli in this recorded version of the PSI. Those children achieving 80% correct sentence identification or better in the quiet condition are further assessed in the presence of single-talker competition over a range of message-to-competition ratios (MCR), including +10 dB MCR (the competition is 10 dB less intense than the message), 0 dB MCR (the competition and message are at the same presentation level) and –10 dB MCR (the competition is 10 dB more intense than the message). Competing sentences are delivered via loudspeaker located 90° to the nonimplanted side of the child. The child is required to achieve a minimum score of 20% at one MCR before proceeding to the next, more difficult condition.

The PSI protocol differs for the NH controls. To ensure that the NH children are able to complete a sentence identification task, it is first required that they correctly identify five out of five sentences in quiet before the more difficult competing conditions are initiated. In competition, children are assessed first at the most difficult listening condition (–10 dB MCR), regressing to less difficult tests

only when scores of 100% are not achieved. This deviation from protocol is instituted for increased efficiency, with scores of 100% imputed for the untested easier conditions so as not to underestimate performance by the NH group. The decision to impute is supported by data obtained from a subset of NH children who were administered the entire protocol and demonstrated little to no deviation from ceiling performance under the less rigorous listening conditions.

Procedure

With the exception of the IT-MAIS and MAIS, all tests were administered in a sound-attenuating booth, with the stimuli (live voice or recorded) presented in the sound field. Recorded stimuli were routed via compact disc to an audiometer for amplification and delivered to a loudspeaker. Presentation levels were delivered at 70 dBA. Baseline testing for the CI group (before implant surgery) was conducted with hearing aid(s) activated. The volume and sensitivity settings for the sensory devices were adjusted to typical use setting.

Results

For each of the three measures, the mean scores for the NH and CI groups are presented at each test interval (baseline, 6 months, and 1 year) in figures 1–4. The num-

Fig. 1. Mean scores, in percent, for the combined IT-MAIS and MAIS obtained by parent interview for NH and CI children at three test intervals (baseline, 6 months, and 1-year follow-up). The number of children assessed at each test interval is indicated in each data bar. The error lines represent 1 standard deviation of the mean.

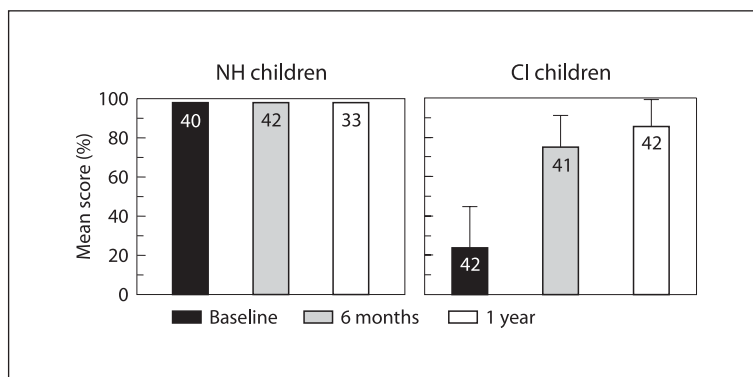


Fig. 2. Mean ESP categories achieved by NH and CI children at three test intervals (baseline, 6 months, and 1-year follow-up). The number of children assessed at each test interval is indicated in each data bar. The error lines represent 1 standard deviation of the mean.

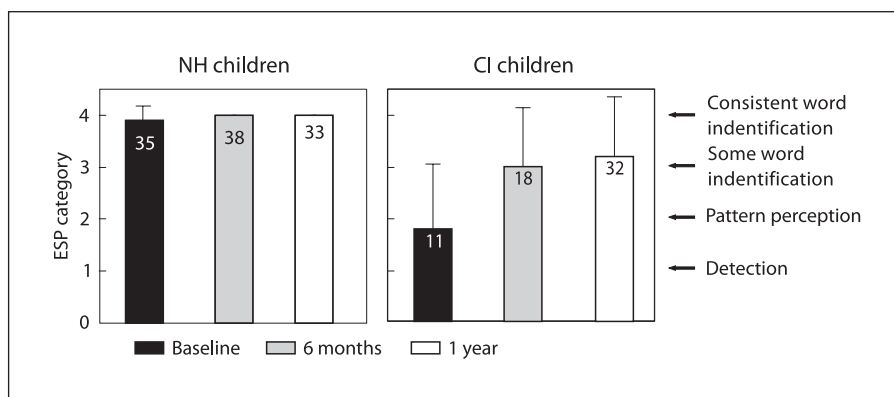
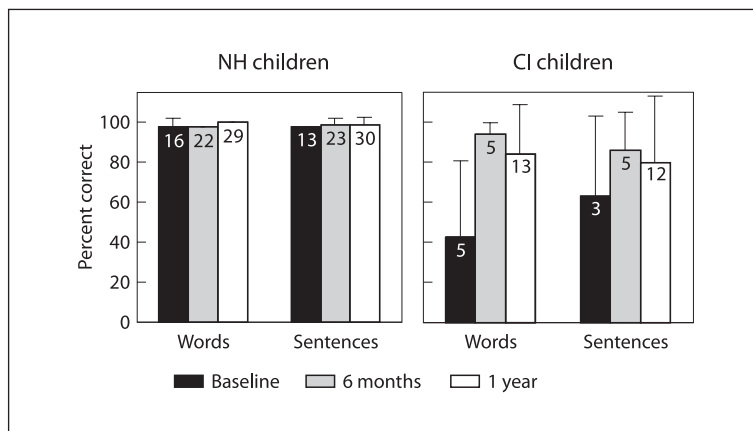


Fig. 3. Mean PSI word and sentence identification scores in the quiet condition for NH and CI children at three test intervals (baseline, 6 months, and 1-year follow-up). The number of children assessed at each test interval is indicated in each data bar. The error lines represent 1 standard deviation of the mean.



ber of participants is indicated in each data bar. These numbers vary across test measures, subject groups, and test intervals as a consequence of the hierarchical approach and differences in children’s ages and functional hearing abilities.

Meaningful Auditory Integration Scale (IT-MAIS and MAIS)

A greater number of children were assessed on the IT-MAIS compared to the MAIS, reflecting the young age

of this sample. For the NH group, responses to the IT-MAIS were obtained from 30 children at baseline (mean score = 98%), 30 children at 6 months (mean score = 97%), and 22 children at 1 year (mean score = 97%). MAIS data were obtained from 10 NH children at baseline (mean score = 99%), 12 children at 6 months (mean score = 99%), and 11 children at 1 year (mean score = 100%).

For the CI group, responses to the IT-MAIS were obtained from 38 children at baseline (mean score = 20%),

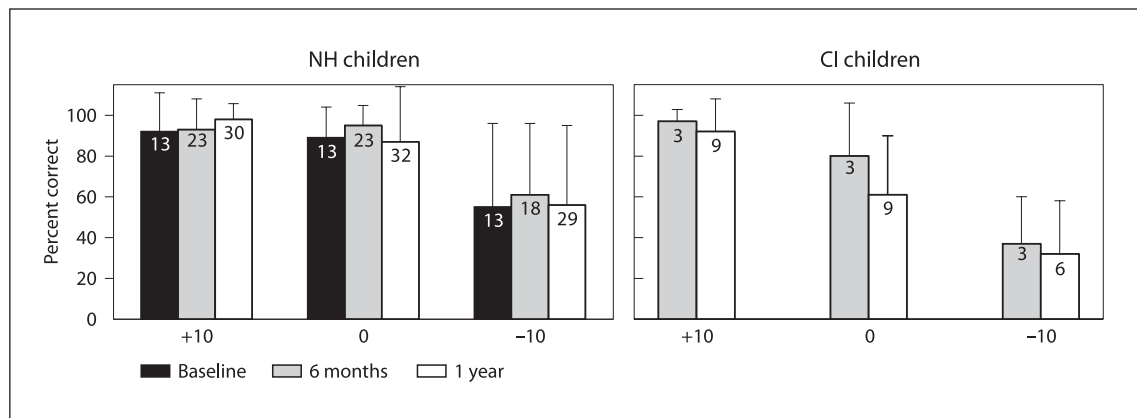


Fig. 4. Mean PSI sentence identification scores across three MCRs for NH and CI children. The number of children assessed at a given MCR (+10, 0, and -10 dB) and at each test interval (baseline, 6 months, and 1-year follow-up) is indicated in each data bar. The error lines represent 1 standard deviation of the mean.

33 children at 6 months (mean score = 74%), and 28 children at 1 year (mean score = 85%). MAIS responses were obtained from 4 children at baseline (mean score = 59%), 8 children at 6 months (mean score = 79%), and 14 children at 1 year (mean score = 84%).

In view of the fact that the two scales tap into the same abilities, results from the two versions of the test were combined for ease of display and analysis. As shown in figure 1, the NH controls were essentially at ceiling, with a mean score of 98% across the three test intervals. The reduced number of data points at 1-year follow-up was attributed to ceiling scores of 100% attained at the two previous test intervals.

The CI group achieved a mean score of 24% at baseline, which improved to 75% at 6 months and 85% at 1 year. Paired t tests conducted on arcsine-transformed data confirmed that 6-month scores were significantly higher than those at baseline for the CI group ($t_{40} = 14.0$, $p < 0.001$), as were scores at 1 year relative to 6 months ($t_{40} = 5.1$, $p < 0.001$). Inspection of individual data indicated that 20 (48%) of the 42 children in the CI group attained 90–100% by 6 months or 1 year.

Early Speech Perception Test (ESP)

For the NH group, data from the low verbal version of the ESP were obtained from 18 children at baseline (mean category score = 3.94), 17 children at 6 months (mean category score = 4.0), and 5 children at 1 year (mean category score = 4.0). Data from the standard version of the ESP were obtained from 17 NH children at baseline (mean category score = 3.88), 21 children at 6 months

(mean category score = 4.0), and 27 children at 1 year (mean category score = 4.0).

For the CI group, category scores from the low verbal ESP were obtained from 10 children at baseline (mean category score = 1.7), 12 children at 6 months (mean category score = 2.58), and 20 children at 1 year (mean category score = 2.75). Category scores from the standard ESP were obtained from 1 CI child at baseline (category score = 3.0), 6 children at 6 months (mean category score = 3.83), and 12 children at 1 year (mean category score = 3.92).

The category scores from the two versions of the test were combined and the mean data are shown in figure 2. With the exception of 3 children with normal hearing who achieved a minimum score of category 3 (some word identification) at baseline, all other NH controls attained category 4 (consistent word identification) across the three test intervals. The 3 children who were assigned a category score of 3 could not be tested on the more difficult monosyllabic subtest (category 4) due to attention and cooperation issues.

The mean category score for the 11 CI children tested at baseline was 1.8 (approaching pattern perception). The 18 CI children tested at 6 months attained a mean score of 3.0 (some word identification). Thirty-two CI children assessed at 1 year achieved a mean score of 3.2 (some word identification). The improvement in category scores at 6 months was statistically significant when compared to baseline scores ($z = -2.07$, $p = 0.038$), as was the improvement at 1 year relative to 6 months ($z = -2.058$, $p = 0.04$). Notably, 20 (48%) of the 42 children in the CI

group achieved category 4 (consistent word identification) by 6 months or 1 year.

Pediatric Speech Intelligibility Test (PSI)

Percent-correct scores on the PSI are presented for words and sentences in quiet (fig. 3) and sentences in competition (fig. 4). Recall that children were eligible for this test if they were 3 years of age and had achieved category 3 or 4 on the ESP. However, 2 NH children and 2 CI children younger than 3 years were assessed on the PSI because they had successfully attained category 4 on the ESP.

PSI in Quiet

In the quiet listening condition, the NH group attained mean word identification scores of 98% both at baseline and 6 months, and 100% at 1 year. For sentences in quiet, performance by children in the NH group was at or near ceiling, with mean scores of 98% at baseline and 99% at 6 months and 1 year.

Mean word identification in quiet for the CI group was 43% (n = 5) at baseline, improving to 94% (n = 5) at 6 months and 85% (n = 13) at 1 year. Mean sentence identification was 63% (n = 3) at baseline, 86% (n = 5) at 6 months, and 80% (n = 12) at 1 year. Ten (24%) of the 42 children in the CI group achieved scores of 90% or better on word and/or sentence identification by either 6 months or 1 year.

PSI in Competition

In speech competition, sentence identification scores for children in the NH group approached ceiling across the three test intervals at +10 dB and 0 dB MCR, with mean scores ranging between 87 and 99%. At -10 dB MCR, mean scores ranged from 55 to 61% across intervals, with 8 (19%) children attaining scores of 100%.

No child in the CI group could be assessed at baseline on sentence identification in competition. By 6 months, mean scores of 97% at +10 dB, 80% at 0 dB, and 37% at -10 dB MCR were attained by 3 CI children. It should be noted that sentence scores at +10 dB and 0 dB MCR were higher than sentence scores in quiet (fig. 3). This finding is due to the fact that only those children achieving scores of 80% or higher in quiet (n = 3) progressed to testing in competition. At 1-year follow-up, mean scores for the CI group were 92% at +10 dB (n = 9), 61% at 0 dB (n = 9), and 32% at -10 dB MCR (n = 6). The CI group performed similarly to the NH group at +10 dB MCR, and began to approach performance levels of the NH group at 0 dB MCR. The between-group scores were most discrepant at

-10 dB MCR (most difficult listening condition), although this difference did not reach statistical significance on nonparametric analysis (Mann-Whitney U). Remarkably, 3 (7%) of the 42 CI children achieved scores of 50–60% at -10 dB MCR by 6 months or 1 year, similar to those achieved by the NH subjects as a group.

Discussion

Three major findings emerged from this 1-year analysis of speech recognition in a sample of CI and NH children from the national CDaCI study. The first finding relates to the utility of the speech recognition hierarchy in describing the auditory abilities of these children. Considering the range of developmental abilities represented by children in this study, it was not possible or desirable to assess every child on each measure. Rather, the goal was to assess a given child's level without focusing efforts on measures that were either too easy or too difficult. An increasing number of children in the CI group progressed to more difficult tasks of closed-set speech identification in the preschool battery at successive intervals, indicating that the hierarchical approach was a practical strategy for children of this age and with this degree of hearing loss. Although it was yet not possible to determine whether children became testable on a specific measure because of maturation, hearing ability, language skills or a combination of these factors, a cursory inspection of individual data suggested that these children were more capable of performing the auditory tasks following implant intervention than they were at baseline regardless of age at time of testing. The fact that the NH group achieved scores near ceiling provided further verification that the measures selected in the preschool battery were developmentally appropriate. In future reports, growth-curve analyses will be valuable in providing more conclusive evidence to support or refute these early observations.

The second key result was that a number of children in the CI group who met criteria for testing approached levels of performance comparable to those of the NH controls for most of the early measures in the hierarchy. This outcome is particularly relevant considering that this is the first large-scale multicenter pediatric implant investigation to incorporate an NH control group. In earlier longitudinal investigations, control groups consisted of children with profound hearing loss [Geers and Moog, 1991; Osberger et al., 1991] and, more recently, children with moderate to severe hearing loss [Eisenberg et al., 2004]. Therefore, it is significant that an NH control group now

serves as the gold standard for comparison, representing a major shift in expectations for deaf children with CIs.

At the same time, we recognize that comparisons in mean scores between NH and testable CI children may represent artifact of testing methods. Within any one stratum of our testing hierarchy, true differences in speech recognition capacity may be concealed by ceiling effects that constrain scores for the better performing group. For this reason it is important to have a cohort study design that assesses CI children's performance on speech recognition tests of increasing stringency over time. Use of this cohort study should determine (a) whether initial patterns of performance will be maintained as a greater number of children progress to more difficult tasks that require open-set speech recognition, and (b) whether there is correspondence between the age at which a test can first be administered and the ultimate level of performance within strata and within the overall hierarchy. At such a point in data collection, performance within strata can be compared with greater refinement.

Speech recognition ability after cochlear implantation has always been characterized by a high degree of variability, and the present study is no exception. It is expected that both suspected and unsuspected factors will emerge in future analyses to explain why some children in the CI group perform as well as the NH controls. It further remains to be seen whether these initial patterns of performance will be maintained as a greater number of children progress to more difficult tasks that require open-set speech recognition.

The third major finding of this study was that some children in the CI group were able to identify sentences in speech competition within the 1st year of implant use; several of these children attained scores similar to the NH average for the most adverse listening condition (-10 dB MCR). To our knowledge, this is one of the first reports of preschool-age children with CIs being assessed on tasks involving semantic distraction. This assessment is important because children rarely listen in quiet environments and the inclusion of speech competition provides face validity. Moreover, the addition of a semantic distractor increases the perceptual demand as the child must attend selectively to the target while inhibiting linguistic interference from the competing talker [Carhart et al., 1969; Hall et al., 2002]. The ability to understand speech in competition is developmental and approaches asymptote in adolescence [Elliott, 1979; Johnson, 2000; Mills, 1975]. Continued assessment of speech in competition will likely provide some of the most compelling evidence toward addressing the overall hypothesis that young deaf chil-

dren with CIs process spoken words using the same linguistic constraints as those used by children with normal hearing.

Conclusion

A hierarchical approach for evaluating speech recognition has been developed for the CDaCI study to address the challenge of assessing CI and NH cohorts demonstrating an extremely wide range of perceptual capabilities in early childhood. At this stage of the investigation, data have been analyzed for the earliest measures of the speech recognition hierarchy in 42 pairs of children that have reached 1 year of follow-up. An increasing number of preschool-age children met age and performance criteria for assessment of more complex speech stimuli over time. Within 1 year, a number of children in the CI group attained levels of performance approaching those of the NH controls and could identify sentences in speech competition under increasingly difficult listening conditions.

The speech recognition hierarchy is proving to be a practical strategy for tracking emergent skills in young children with CIs. As both groups mature and are assessed on more challenging measures of the hierarchy, adaptive testing of speech in background competition is anticipated and should be more conducive to direct comparison between groups. Adaptive testing enables measurement in the slope portion of the performance-intensity function and, therefore, is not susceptible to floor and ceiling effects. Continued follow-up with greater numbers of children using more complex stimuli should determine whether these early performance trends are predictive of future growth.

Acknowledgments

This research is funded by a grant from the National Institute on Deafness and Other Communication Disorders of the National Institutes of Health (grant number R01DC004797). We would like to thank the children, their families, the staff and surgeons of the participating centers (House Ear Institute, Johns Hopkins Listening Center, The River School, University of Miami, University of Michigan, University of North Carolina, and University of Texas at Dallas) who contributed to the study. We also thank the Psychometrics Center at the University of Miami and the Data Coordinating Center at Johns Hopkins University. We are grateful to our External Advisory Committee for their guidance, particularly Karen Iler Kirk, PhD, for her expertise in issues related to speech recognition.

Appendix

CDaCI Investigative Team

House Ear Institute, Los Angeles: Laurie S. Eisenberg, PhD, CCC-A (PI); Karen Johnson, PhD, CCC-A (coordinator); Traci Critton, PhD (data collection); Jean DesJardin, PhD (data collection); Melinda Gillinger (data collection); William Luxford, MD (surgeon); Amy Martinez, MA, CCC-A (data collection); Louise Mebane, PhD (data collection); Jennifer Regnery, M.S. (data collection); Leslie Visser-Dumont, MA, CCC-A (data collection).

Johns Hopkins University, Listening Center, Baltimore: John K. Niparko, MD (PI); Jennifer Mertes, AuD, CCC-A (coordinator); Steve Bowditch, MS, CCC-A (data collection); Jill Chinnici, MA, CCC-A (data collection); Howard Francis, MD (surgeon); Rick Ostrander, EDD (data collection); Jennifer Yeagle, Med, CCC-A (data collection).

Johns Hopkins University, The River School, Washington, DC: Nancy Mellon (administration); Mary O'Leary Kane, MA, CCC-SLP (coordinator); Sarah Wainscott (data collection); Jennifer Wallace, MS, CCC-SLP (data collection).

University of Miami, Miami: Annelle Hodges, PhD (PI); Thomas Balkany, MD (surgeon); Alina Lopez, MA, CCC-SLP/A (coordinator); Leslie Goodwin, MSN, CCRC (data collection); Stacy Payne, MA, CCC-A (data collection).

University of Michigan, Ann Arbor: Teresa Zwolan, PhD (PI); Amy Donaldson, MA, CCC-A (coordinator); H. Alexander Arts, MD (surgeon); Brandi Butler, MA, CCC-A (data collection); Husam El-Kashlam, MD (surgeon); Krista Heavner, MS, CCC-SLP (data collection); Mary Beth O'Sullivan, MS, CCC-A (data collection); Steve Telian, MD (surgeon); Ellen Thomas, MA, CCC-SLP (data collection); Anita Vereb, MS, CCC-A (former coordinator).

University of North Carolina, Carolina Children's Communicative Disorders Program, Chapel Hill: Carolyn J. Brown, MS (PI); Holly F.B. Teagle, AuD, (coordinator); Craig A. Buchman, MD (surgeon); Carlton Zdanski, MD (surgeon); Hannah Eskridge, MSP (data collection); Harold C. Pillsbury, MD (surgeon).

University of Texas at Dallas, Callier Advanced Hearing Research Center, Dallas: Emily A. Tobey, PhD, CCC-SLP (PI); Betty Loy, AuD, CCC-A (coordinator); Paul Bauer, MD (surgeon); Angela Boyd, BA (data collection); Laura Cantu, BS (data collection); Carol Cokely, PhD, CCC-A (data collection); Sarah Florence, MS, CCC-A (data collection); Janee Gisclair, MS, CCC-A (data collection); Laura Levitan, BA (data collection); Joy Penrad (data collection); Shannon Raby, MA, CCC-SLP (data collection); Jamie Rasmus, BS (data collection); Peter Roland, MD (surgeon); Heather MacFadyen, MS, CCC-SLP (data collection); Donise Pearson, MS, CCC-SLP (data collection); Deborah M. Rekart, PhD (former coordinator); Lauren Sacar, BA (data collection); Melissa Sweeney, MS, CCC-SLP (data collection); Linsey Wagner, BA (data collection); Nicole Weissner, BA (data collection); Berkley Williams, MA, CCC-SLP (data collection).

Resource Centers

Data Coordinating Center, Johns Hopkins University, Welch Center for Prevention, Epidemiology & Clinical Research, Baltimore: Nancy E. Fink, MPH (PI); Patricia Bayton (data assembly); Laura Plantinga, ScM (data assembly); Neil R. Powe, MD, MPH, MBA (co-PI); Thelma Vilche (data assembly); Nae-Yuh Wang, PhD (data assembly and analysis).

Psychometrics Center, University of Miami, Department of Psychology, Coral Gables: Alexandra Quittner, PhD (PI); David Barker (data analysis); Pam Leibach (data analysis); Ivette Cruz (data analysis).

Study Oversight Committees

Executive Committee: John K. Niparko, MD (chair); Laurie S. Eisenberg, PhD; Nancy E. Fink, MPH; Alexandra L. Quittner; Emily A. Tobey, PhD.

External Advisors: Noel Cohen, MD; Julia Evans, PhD; Ann Geers, PhD; Karen Iler Kirk, PhD.

References

- Berliner KI, Eisenberg LS, House WF (eds): The cochlear implant for children: an auditory prosthesis for the profoundly deaf child. *Ear Hear* 1985;6(suppl):1S-69S.
- Boothroyd A: Developmental factors in speech recognition. *Int J Audiol* 1970;9:30-38.
- Boothroyd A, Boothroyd-Turner D: Postimplantation audition and educational attainment in children with prelingually acquired profound deafness. *Ann Otol Rhinol Laryngol* 2002; 111(suppl 189):79-84.
- Carhart R, Tillman T, Greetis R: Perceptual masking in multiple sound backgrounds. *J Acoust Soc Am* 1969;45:694-703.
- Colletti V, Carner M, Miorelli V, Guida M, Colletti L, Fiorino FG: Cochlear implantation at under 12 months: report on 10 patients. *Laryngoscope* 2005;113:445-449.
- Eisenberg LS, Berliner KI, Thielemeir MA, Kirk KI, Tiber N: Cochlear implants in children. *Ear Hear* 1983;4:41-50.
- Eisenberg LS, Dirks DD: Reliability and sensitivity of paired comparisons and category rating in children. *J Speech Hear Res* 1995;38:1157-1167.
- Eisenberg LS, Kirk KI, Martinez AS, Ying EA, Miyamoto RT: Communication abilities of children with aided residual hearing: comparison with cochlear implant users. *Arch Otolaryngol Head Neck Surg* 2004;130:563-569.
- Elliott LL: Performance of children aged 9 to 17 years on a test of speech intelligibility in noise using sentence material with controlled word predictability. *J Acoust Soc Am* 1979;80: 1250-1255.
- Franz DC: Pediatric performance with the Med-El Combi 40+ cochlear implant system. *Ann Otolaryngol Rhinol Laryngol* 2002;111(suppl 189):66-68.
- Geers AE: Techniques for assessing auditory speech perception and lipreading enhancement in young deaf children; in Geers AE, Moog JS (eds): *Effectiveness of Cochlear Implants and Tactile Aids for Deaf Children: The Sensory Aids Study at Central Institute for the Deaf*. *Volta Rev* 1994;96:85-96.
- Geers AE, Moog JS: Evaluating the benefits of cochlear implants in an educational setting. *Am J Otol* 1991;12(suppl):116-125.
- Gelnett D, Sumida A, Nilsson M, Soli SD: Development of the Hearing in Noise Test for Children (HINT-C). *Annu Meet Am Acad Audiol*, Dallas, 1995.
- Hall JW, Grose JH, Buss E, Dev MB: Spondee recognition in a two-talker masker and a speech-shaped noise masker in adults and children. *Ear Hear* 2002;23:159-165.
- Haskins H: A phonetically balanced test of speech discrimination for children; unpubl. master's thesis, Evanston, 1949.

- James AL, Papsin BC: Cochlear implant surgery at 12 months of age or younger. *Laryngoscope* 2004;114:2191–2195.
- Jerger S, Jerger J: *Pediatric Speech Intelligibility Test*. St. Louis, Auditec of St. Louis, 1984.
- Johnson C: Children's phoneme identification in reverberation and noise. *J Speech Lang Hear Res* 2000;43:144–157.
- Kirk KI: Challenges in the clinical investigation of cochlear implant outcomes; in Niparko JK, Kirk KI, Mellon NK, Robbins AM, Tucci DL, Wilson BS (eds): *Cochlear Implants Principles & Practices*. Philadelphia, Lippincott Williams & Wilkins, 2000, pp 225–259.
- Kirk KI, Diefendorf AO, Pisoni DB, Robbins AM: Assessing speech perception in children; in Mendel LL, Danhauer JL (eds): *Audiologic Evaluation and Management and Speech Perception Assessment*. San Diego, Singular Publishing Group, 1997, pp 101–132.
- Kirk KI, Pisoni DB, Osberger MJ: Lexical effects of spoken word recognition by pediatric cochlear implant users. *Ear Hear* 1995;16:470–481.
- Mills JH: Noise and children: a review of literature. *J Acoust Soc Am* 1975;58:767–779.
- Moog JS, Geers AE: *Early Speech Perception Test for profoundly hearing-impaired children*. St. Louis, Central Institute for the Deaf, 1990.
- Osberger MJ, Koch DB (eds): Clinical results with the Clarion multi-strategy cochlear implant. *Ann Otol Rhinol Laryngol* 1999;108(suppl 177):1–128.
- Osberger MJ, Robbins AM, Miyamoto RT, Berry SW, Myres WA, Kessler KS, Pope ML: Speech perception abilities of children with cochlear implants, tactile aids, or hearing aids. *Am J Otol* 1991;12(suppl):105–115.
- Osberger MJ, Zimmerman-Phillips S, Koch DB: Cochlear implant candidacy and performance trends in children. *Ann Otol Rhinol Laryngol* 2002;111(suppl 189):62–65.
- Robbins AM, Renshaw JJ, Berry SW: Evaluating meaningful auditory integration in profoundly hearing-impaired children. *Am J Otol* 1991;12(suppl):144–150.
- Staller SJ (ed): *Multichannel cochlear implants in children*. *Ear Hear* 1991;12(suppl):1S–89S.
- Staller S, Parkinson A, Arcaroli J, Arndt P: Pediatric outcomes with the Nucleus 24 Contour: North American clinical trial. *Ann Otol Rhinol Laryngol* 2002;111(suppl 189):56–61.
- Waltzman SB, Roland JT: Cochlear implantation in children younger than 12 months. *Pediatrics* 2005;116:e487–e493.
- Zimmerman-Phillips S, Robbins AM, Osberger MJ: Assessing cochlear implant benefit in very young children. *Ann Otol Rhinol Laryngol* 2000;109(suppl 185):42–43.