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Cochlear Implantation in Deaf Infants

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Objectives: **With the application of universal newborn hearing screening programs, a large pool of newly identified deaf infants has been identified. The benefits of early intervention with cochlear implants (CI) is being explored. Mounting evidence suggests that age at implantation is a strong predictor of language outcomes. However, new behavioral procedures are needed to measure speech and language skills during infancy. Also, procedures are needed to analyze the speech input to young CI recipients.** ***Study Design:*** **Cohort-sequential.** ***Methods:*** **Thirteen infants with profound hearing loss who were implanted between the ages of 6 to 12 months of age participated in this study. Eight participated in two new behavioral methodologies: 1) the visual habituation procedure to assess their discrimination of speech sounds; 2) the preferential looking paradigm to assess their ability to learn associations between speech sounds and objects. Older implanted infants and normal-hearing infants were also tested for comparison. The pitch of mothers' speech to infants was analyzed.** ***Results:*** **Patterns of looking times for the very early implanted infants were similar to those of normal hearing infants. Mothers' speech to infants with CIs was similar in pitch to normal-hearing infants who had the same duration of experience with sounds.** ***Conclusions:*** **No surgical or anesthetic complications occurred in this group of infants, and the pattern of listening skill development mirrors that seen in normal-hearing infants. Mothers adjust their speech to suit the listening experience of their infants.** ***Key Words:*** **Cochlear implants, infants, deafness, behavioral measures.**

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INTRODUCTION

As a result of detailed longitudinal studies of speech and language skills in children who have received cochlear implants (CI) at various ages, increased enthusiasm for early intervention with implants has emerged. Age at implantation appears to be a strong predictor of language outcomes. Children who receive CIs at younger ages tend to outperform children who receive implants later. Lowering the age limit below age 1 year is currently being explored. We have implanted 13 children below the age of 1 year and have developed assessment tools to quantify their performance.

Cochlear implantation in infancy requires very careful attention to the delicate scalp, the thin skull, and the small dimensions of the incompletely developed mastoid. We have used a minimal retroauricular skin incision (4–5 cm) and placed the implant package in a pericranial pocket without exposing dura. Although the mastoid process is incompletely developed, the mastoid antrum and the facial recess are usually adequately developed to provide access to the middle ear. The target organ, the cochlea, is already in its adult configuration at birth and can accept any of the currently available electrode arrays. In the hands of experienced pediatric anesthesiologists, the anesthetic risks are not greater in 6-month-old infants than in 12-month-old infants. In our cohort of 13 infants implanted before the age of 1 year, we have experienced no surgical, anesthetic, or postoperative pulmonary complications. There have been no facial nerve injuries or problems with the skin overlying the implant package.

The assessment of speech and language skills in infants requires new behavioral methodologies. The clinical tests previously used for assessing implanted children's speech perception and language skills require the children to follow verbal instructions. Infants have not yet acquired these skills. To address this need, modified versions of the visual habituation (VH) procedure and the preferential looking paradigm (PLP) have been applied. We will also explore acoustic characteristics of mothers' speech to infants who use CIs.

MATERIALS AND METHODS

Participants

Twenty-six infants with congenital profound hearing loss (HL) participated. Eight of the participants (4 female, 4 male) received a CI before 12 months of age and had no other developmental impairments. Their age at implantation ranged from 6.38 months to 10.85 months with a mean of 9.19 months. Seventeen infants (6 female, 11 male) received a CI between 12 and 24 months of age. Their age at implantation ranged from 12.39 months to 23.24 months with a mean of 17.71 months. Table 1 provides additional demographic information. All infants showed a mean pure-tone average auditory detection of 50 dB HL or better within the first 3 months after CI (measured by visual reinforcement audiometry).

Behavioral Testing

Infants were tested using two behavioral methodologies that have been successful for investigating speech perception and language skills in infants with normal hearing.[1] The VH procedure was used to assess infants' discrimination of speech sounds. The PLP was used to assess infants' ability to learn associations between speech sounds and objects, a skill that is important for word learning. Previous reports[2,3] have shown that these methodologies can be used successfully to assess speech perception and language skills of deaf infants who use CIs.

Apparatus

The testing was conducted in a custom-designed, double-walled IAC sound booth. As shown in Figure 1, infants sat on their caregiver's lap in front of a television monitor. All visual stimuli were displayed at the left, right, center, or left and right locations on the television monitor at approximately eye level to the infant, and the auditory stimuli were presented through both the left and right loudspeakers of the television monitor. The experimenter observed the infant from a separate room by way of a hidden, closed-circuit television camera and controlled the experiment using the Habit software package[4] running on a Macintosh desktop computer.

Stimulus Materials

Speech stimuli. For both the VH and the PLP, we used a contrast that is among the first contrasts that hearing-impaired listeners are able to discriminate:[5] a continuous steady-state vowel /a/ ("ahhh") versus eight repetitions of /hap/ ("hop"). The stimuli were produced by a female talker and were presented to the infants at 70 ± 5 dB SPL by way of loudspeakers on the television monitor.

Visual stimuli. A silent video of an infant laughing was used to bring the infants' attention to the television before the presentation of experimental stimuli. For the VH, the same visual display of a red and white checkerboard pattern was paired with each of the speech stimuli and appeared at the center location of the television monitor. For the PLP, each speech sound was paired with a dynamically changing visual event. The /a/ was paired with a video of a toy airplane moving horizontally across a table. The repetitions of /hap/ were paired with a video of a toy kangaroo hopping up and down. The videos were edited so that they appeared at the left and right locations of the television monitor.

TABLE I.
Demographic Information for Infants Implanted before 12 Months of Age (E1–E8) and between 12 and 24 Months of Age (L1–L28).

Subject	Sex	Etiology of Hearing Loss	Age at Surgery (months)	Age at CI Activation (months)	Implant	Processor	Processing Strategy	Comm. Mode
E1	M	Unknown	6.38	7.59	N24	Sprint	ACE	Oral
E2	F	Unknown	7.3	8.29	N24	Sprint	ACE	Total
E3	F	Unknown	8.45	10.29	Med-El	Tempo	CIS	Total
E4	F	Unknown	9.73	11.08	N24	Sprint	ACE	Total
E5	M	Auditory Neuropathy	9.76	10.75	N24	Sprint	ACE	Oral
E6	M	Unknown	10.36	11.83	N24	Sprint	ACE	Oral
E7	M	Unknown	10.68	12.72	N24	Sprint	CIS	Total
E8	F	Unknown	10.85	12.20	N24	Sprint	ACE	Oral
L1	M	Genetic	12.39	13.87	N24	Sprint	ACE	Oral
L2	M	Auditory Neuropathy	12.62	13.77	N24	Sprint	ACE	Oral
L3	M	Unknown	15.06	16.11	N24	Sprint	ACE	Oral
L4	F	Unknown	15.35	17.42	N24	Sprint	ACE	Oral
L5	M	Unknown	15.45	16.50	Med-El	Tempo+	CIS+	Oral
L6	M	Unknown	15.52	16.96	N24	Sprint	ACE	Total
L7	M	Unknown	15.61	16.80	N24	Sprint	ACE	Total
L8	M	Unknown	16.21	17.14	Med-El	Tempo+	CIS+	Oral
L9	F	Unknown	16.27	17.29	N24	Sprint	ACE	Oral
L10	F	Unknown	17.65	19.07	N24	Sprint	ACE	Oral
L11	M	Unknown	19.13	20.09	Med-El	Tempo	CIS	Total
L12*	F	Mondini	19.05	20.92	N24	Sprint	ACE	Oral
L13	F	Mondini	20.51	21.66	Med-El	NA	NA	Total
L14	F	Unknown	20.81	21.73	N24	Sprint	ACE	Total
L15	M	Unknown	21.01	22.45	N24	Sprint	ACE	Oral
L16	F	LVA	21.99	23.67	Clarion	PSP	MPS	Total
L17	M	Unknown	22.22	24.16	N24	Sprint	ACE	Oral
L18	M	Unknown	23.24	24.28	N24	Sprint	ACE	Total

Bolded participant codes indicates participation in mothers' speech to infants study. All infants participated in behavioral testing except L12*. Communication mode describes whether infants use exclusively spoken language (oral) or a combination of spoken language with Signed Exact English (total).

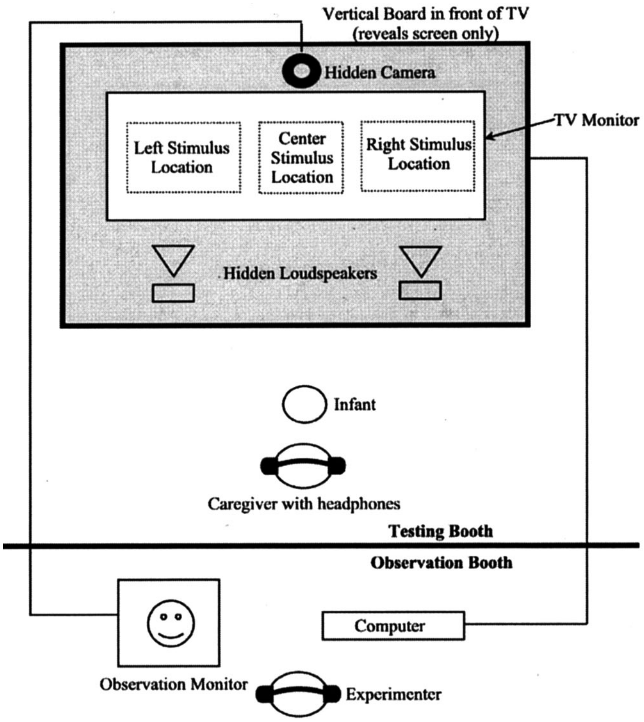

Fig. 1. Testing apparatus for behavioral measures.

Procedure

Infants with CIs were tested at several intervals after cochlear implantation. These intervals were separated into three interval groups. Interval group 1 consisted of tests conducted at 1 day, 1 week, and 1 month after implantation. Interval group 2 consisted of testing at 2 months, 3 months, and 6 months after implantation. Interval group 3 consisted of testing at 9 months, 12 months, and 18 months after implantation. All infants completed at least one testing session within at least two interval groups. Approximately 20% of the test sessions for both the VH and the PLP could not be completed by the infants because of crying, fussiness, or equipment malfunctions. The experimenter and parents checked the CI of the infant before testing to make sure it was functioning properly.

The VH procedure consists of two phases. During the habituation phase, infants were presented with a visual display of a checkerboard pattern on every trial. On half of the trials, the visual display was paired with one of the speech sounds.[1] The other half of the trials were silent. Infants were presented with "sound" and "silent" trials to access their sustained attention to speech. The attentional component of this experiment is not reported here because it falls outside the scope of this paper. Each trial lasted until the infant looked away for 1 second or more, whereon the speech sound stopped and visual display disappeared until the initiation of the next trial. The habituation phase continued until the infant reached the habituation criterion: a mean looking time over a block of four trials that was 0.5 the mean looking time during the first four trials.

After habituation, infants were presented with two trials during a test phase. During the "old" trial, infants were presented with the same speech sound as presented during habituation. During the "novel" trial, infants were presented with the other sound of the contrast. The order of the novel and old trials was counterbalanced across infants and testing sessions. Infants' discrimination of the speech sounds was measured by the difference in looking time to the novel trial versus the old trial.

The PLP consisted of two types of trials: learning trials and test trials. During learning trials, infants were presented with one of the videos and the speech sound that corresponded with the video (e.g., repeating /hap/ with the video of a bouncing kangaroo). During the test trials, infants were presented with both videos, one on the left and one on the right, and one of the speech sounds. For half of the test trials, the speech stimulus corresponding with the video on the left was presented, and for the other test trials, the other speech stimulus was presented.

For each infant, the order of stimulus presentation was as follows: 8 learning trials, 4 test trials, 2 learning trials, 4 test trials, 2 learning trials, 4 test trials, 2 learning trials, 4 test trials. We intermixed the trials to remind infants of the correct pairings throughout the testing session. Infants ability to learn the associations between the speech sounds and the objects was measured by the difference in looking time to the video that corresponded to the speech sound ("target" video) versus the video that did not ("nontarget" video). It is predicted that they will look longer to the target video than to the nontarget video if they are able to learn the associations.

Mothers' Speech to Infants

Behavioral testing reveals infants' speech perception abilities, but it does not reveal the types of speech infants are exposed to everyday at home. Because pediatric HL and cochlear implantation may affect the way mothers speak to their children,[6,7] we recorded mothers' speech to eight hearing-impaired infants with CIs (age range: 13–37 months). We also recorded mothers' speech to seven normal-hearing infants in a chronological age-match control group (NH-CA, age range: 13–37 months) and to eight normal-hearing infants in a "hearing age"-match control group (NH-HA, age range: 3–18 months). Hearing age is the number of months an infant has used a CI.

We recorded mothers speaking to their infants or to an experimenter in a sound booth (IAC). In the infant-directed (ID) speech condition, mothers were instructed to speak to their infant as they normally do at home. In the adult-directed (AD) speech condition, an experimenter conducted a short interview with each mother. The AD speech condition was included to provide a baseline of normal speech. We recorded mothers' speech with a hypercardioid microphone (Audio-Technica ES933/H) powered by a phantom power source. The microphone was linked to an amplifier (DSC 240) and a digital/audio tape recorder (Sony DTC-690).

In this preliminary analysis, the acoustic feature that most typically characterizes mothers' speech to infants, fundamental frequency (Hz), was measured using Praat software.[8] The mean fundamental frequency was obtained for each utterance in a 2 minute speech sample in ID and AD conditions and averaged across utterances. An utterance was defined as a complete sentence or a complete thought.

RESULTS

Behavioral Testing

VH procedure. For the measure of discrimination, the difference in looking times to the novel trials versus the old trials was submitted to a mixed model with repeated measures. A mixed model is similar to a repeated-measures analysis of variance (ANOVA) but can deal with missing values without eliminating data.[9] In addition to looking time difference, the factors in the model included communication mode (oral only or total communication) and interval group. Looking time differences across intervals are displayed in Figure 2. For comparison, looking time differences by normal-hearing infants are also displayed.

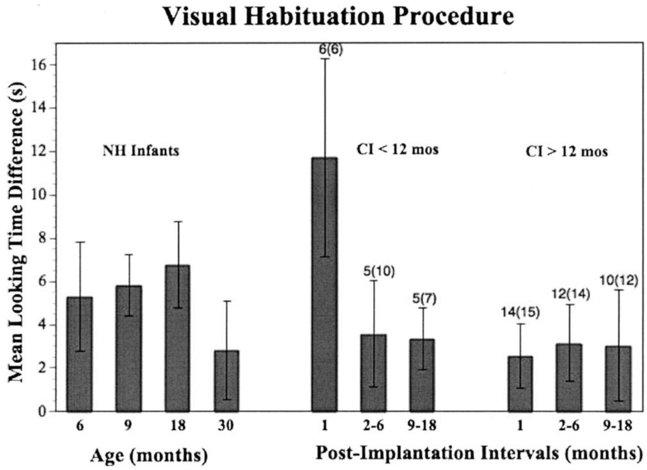

Fig. 2. Mean difference (and SE) in looking time to the checkerboard pattern during the novel trials versus during the old trials in the VH procedure for normal-hearing infants, deaf infants implanted before 12 months of age, and deaf infants implanted between 12 and 24 months of age. For the deaf infants, data are separated by postimplantation interval group, which describes how much experience the infants have had with their cochlear implant after it was activated. For each interval group, the number of infants who completed at least one testing session is indicated above the error bar, with total number of testing session completed in parentheses.

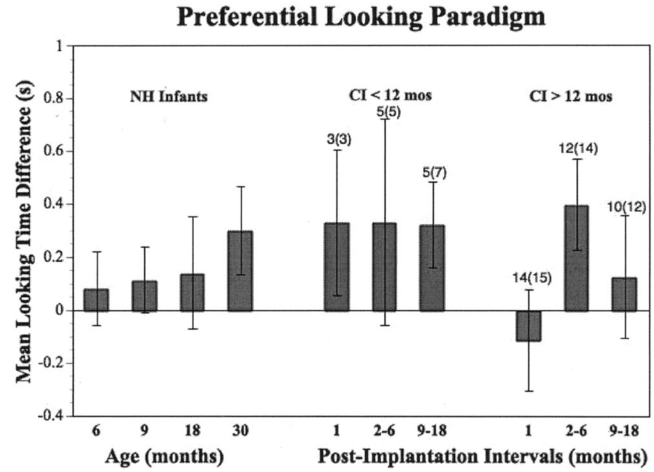

Fig. 3. Mean looking time difference to the target video versus the nontarget video trials in the preferential looking paradigm for normal-hearing infants, deaf infants implanted before 12 months of age, and deaf infants implanted between 12 and 24 months of age.

The analyses revealed longer looking times to the novel versus the old trials for both the infants implanted under 12 months of age ($F(1, 6) = 9.20$, $P = .02$) and those implanted between 12 and 24 months of age ($F(1, 16) = 5.73$, $P = .03$). No other main effects or interactions approached statistical significance. These results suggest that after implantation, deaf infants are able to discriminate a continuous versus a discontinuous sound pattern.

PLP. A mixed model with repeated measures was used again to perform analyses of the looking time differences to the target versus the nontarget videos. Analyses revealed significantly longer looking times to the target versus the nontarget for the infants implanted under 12 months of age ($F(1, 7) = 6.45$, $P = .04$). However, infants implanted between 12 and 24 months of age did not exhibit longer looking times to the target versus the nontarget ($F(1, 14) = 0.16$, $P = .7$). There were no other significant main effects or interactions, suggesting that testing interval and communication mode did not have an effect on this task. Looking time differences to the target versus the nontarget for each stimulus condition and across intervals is shown in Figure 3. Data from normal-hearing infants are also presented for comparison. Normal-hearing infants' preference for the target increased with age, suggesting that infants improve in this task across development. Thus, the findings that earlier-implanted deaf infants show more consistent preference for the target than the older, later-implanted deaf infants provides strong evidence that earlier-implanted infants performed better (relative to their age) than later-implanted infants.

Taken together, the findings from the two behavioral tasks suggest that very soon after cochlear implantation, young deaf infants are able to discriminate continuous versus discontinuous speech sounds. Also, infants implanted under 12 months of age were able to learn associations between speech sounds and objects. Infants implanted after 12 months of age did not show consistent learning of the associations within the context of this experiment. It is possible that they would be able to learn the associations if they were given additional repetitions of the pairings between the speech sounds and the objects.

Mothers' Speech to Infants

We compared differences in average fundamental frequency between maternal ID and AD speech for the three mother-infant groups: CI, NH-CA, and NH-HA. Differences rather than absolute values are used because mothers have varying baseline fundamental frequencies. For example, one mother naturally may be higher pitched than another mother, which is unrelated to the hearing level of their children. Previous research leads us to expect that mothers will speak with higher pitch to infants than adults and that the size of this difference should decrease with the age of the infant.[10–12]

Figure 4 shows the differences in fundamental frequency (ID speech minus AD speech) for the three mother-infant groups. Mothers' speech to infants was higher pitched than their speech to adults in all three groups. Nevertheless, an ANOVA revealed a significant main effect of hearing status, $F(2,20) = 5.34$, $P = .014$. A post hoc Tukey test revealed no significant difference in fundamental frequency between the CI and NH-HA groups but significant differences in fundamental frequency between the CI and NH-CA groups and the NH-HA and NH-CA groups. Thus, the size of the pitch difference between ID and AD speech was more similar in mothers' speech to deaf infants with CIs and their hearing age-match controls than to their chronological age-match controls.

The results of the maternal vocal pitch analyses revealed that pitch levels were higher in ID speech than AD speech, regardless of infants' hearing status or chronological age. However, the size of the pitch difference was greater when mothers were speaking to deaf infants with

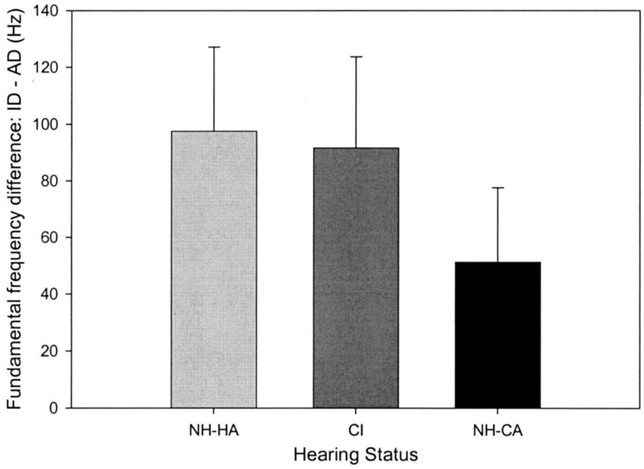

Fig. 4. Average fundamental frequency differences (ID speech minus AD speech) in normal-hearing mothers' speech to deaf infants with cochlear implants (CI), normal-hearing infants matched by hearing age (NH-HA), and normal-hearing infants matched by chronological age (NH-CA). Error bars represent SE.

CIs and normal-hearing infants matched by hearing age than when speaking to normal-hearing infants matched by chronological age. That is, a mother of a 13-month-old hearing-impaired infant who received a CI at 10 months of age (hearing age = 3 months) would speak to her infant using a similar speaking style that a mother would use with a normal-hearing 3-month-old rather than a normal-hearing 13-month-old infant. This result implies that deaf infants who receive CIs at younger ages (i.e., hearing age is closer to chronological age) will be exposed to maternal speech styles more closely matched to their normal-hearing same-age counterparts, which in turn may influence their speech perception and language development.

GENERAL DISCUSSION

We have described methods for assessing infants' speech perception and language skills after implantation and for analyzing the type of speech input they receive. These types of assessments and analyses are valuable for several reasons. First, to determine whether cochlear implantation under 12 months of age provides deaf infants with any advantages in early speech perception and language skills, it is important to use measures that are suitable for infants. The methodologies reported here accomplish this and provided some preliminary findings that very early implantation may facilitate infants' ability to learn associations between speech sounds and objects, a skill that is central to being able to learn words.

Developing infant assessment tools is important also because these tools may eventually provide clinicians with ways of evaluating the success of their therapy strategies with individual patients. It is important to continue to develop behavioral methodologies with the goal of creating more precise and reliable measures to eventually be able to provide reliable information of the speech and language skills of individual infants at specific times.

Analyzing the speech input to infants will potentially provide clinically valuable information. Previous studies have shown that early auditory experiences and vocal speech quality are linked to infants' subsequent development of speech perception, language, and cognitive skills.[13–15] Thus, the present findings could also be developed to determine the optimal speech therapy tools for use with very young infants who receive CIs.

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