Speech discrimination skills in deaf infants before and after cochlear implantation

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Speech discrimination skills in deaf infants before and after cochlear implantation

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Abstract

The benefit of early cochlear implantation (CI) to later speech perception outcomes in prelingually deaf (PLD) children is well established and implantation of infants has become more prevalent. The aim of this study was to determine whether or not deaf infants could discriminate audiovisual non-words shortly after CI and whether their attention to speech and non-speech audiovisual stimuli was similar to infants with normal hearing (NH). Three groups of participants were tested: PLD infants tested prior to CI (pre-CI), PLD infants tested post-implantation (post-CI), and a group of age-matched NH infants. A novel version of the visual habituation (VH) procedure was used. Infants were presented repetitions of an audiovisual non-word until their looking-time decreased to a predetermined criterion. They were then presented two types of test trials: repetitions of the old word (non-alternating (NA) trials) and repetitions of a novel non-word alternating with the old word (alternating (A) trials). Longer looking times to the A relative to the NA trials was taken as evidence of discriminating the non-words. An audiovisual non-speech trial was presented at the beginning and the end of each experiment and looking times between speech and non-speech trials were compared. Analyses revealed that pre- and post-CI infants had significantly shorter looking times than NH infants for speech but not non-speech trials. Furthermore, deaf infants often did not look long enough to be exposed to the novel non-word during the A trials. When trials with less than three seconds of looking were removed, analyses revealed that both NH infants and post-CI infants discriminated the non-words but pre-CI infants did not. Pre-implant hearing, age at implantation, and length of CI use were not related to visual preference for A trials. These results suggest that PLD infants show less visual interest in speech stimuli than NH infants. Despite this, PLD infants appear to be able to discriminate audiovisual non-words within three months after implantation.

Key words: *cochlear implant, infant speech perception, visual habituation, outcomes*

Introduction

Congenital deafness is estimated to occur in 1/1000 infants and an additional number of infants acquire deafness from ototoxicity, meningitis, or other causes (1). Affected infants are deprived of crucial auditory input during the sensitive period for language development and their capacity for developing strong spoken language skills depends on a number of factors (2). For prelingually deaf (PLD) children with bilateral, profound sensorineural deafness, cochlear implants (CIs) have been shown to lead to gains in speech perception, language development, vocabulary, and speech intelligibility (3–5). Nevertheless, most studies have shown that individual variability in spoken-language outcomes is enormous and difficult to predict (6).

Speech perception outcomes of children with CIs

Studies of paediatric CI users who are old enough to follow instructions and respond behaviourally have revealed that speech perception skills improve after implantation, and continue to improve with CI use (7–9). These studies have employed speech perception tests that require some behavioural response such as pointing to a picture or oral or signed responses, and have included both closed and open-set measures. Osberger et al. tested 30 PLD children as young as five years of age at three intervals: pre-implant, three months post-implant, and six months post-implant (8). Children in the three-month post-implant interval performed significantly better than in the pre-implant interval on closed and open set tests of spoken-word recognition, indicating that gains in speech perception begin as early as three months after CI. Kishon-Rabin et al. employed a forced-choice test of phoneme perception to measure speech perception skills in paediatric CI users aged 2.5 to 10 years of age (7). They found that overall phoneme perception scores followed an exponential growth function with a 90% correct asymptote at four years post-implantation. Rate of

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improvement with CI use varied among contrast features with children demonstrating ceiling performance on vowel place immediately after implantation in contrast to voicing that was perceived by chance until two to three years of CI use.

As with other aspects of spoken-language outcomes in paediatric CI users, most studies of speech perception skills have reported a large degree of variability between individual patients (7–9). Several predictive factors have been reported. Children who are immersed in an oral habilitative environment show greater speech perception scores than children who use both manual and oral communication (8,10,11). Kishon-Rabin et al. found a trend for higher phoneme contrast scores in children enrolled in auditory-verbal habilitation compared with the rest of the sample (7). Children with more pre-operative residual hearing show higher speech perception scores than children with less residual hearing (7,8).

Another robust predictor of speech perception in paediatric CI users is age at implantation. Children implanted earlier consistently show higher performance on speech perception measures than children implanted later in life (9–11). This finding has been influential clinically as deaf infants are being implanted at progressively younger ages. Indeed, it is not uncommon for a six-month-old infant to receive a CI at many CI centers with large patient loads. As the implantation of infants has become more prevalent, the need for assessment tools that can assess speech perception skills during infancy has grown substantially. Currently, there are few established methods for testing speech perception skills in deaf infants with CIs. This makes it difficult, if not impossible, to objectively assess benefit from intervention strategies in the youngest CI users. Furthermore, it is difficult without objective behavioural measures of spoken-language skills, to identify and target those infants who are struggling or receiving little benefit from their CI.

Measuring CI outcomes in infants

The pre-linguistic skills of deaf infants are difficult to measure for a number of reasons that stem from infants' inability to comprehend and follow instructions and respond verbally to tests of speech and language. Some researchers have attempted to use the subjective tools used by clinicians to study outcomes from implantation in deaf infants. Questionnaires such as Infant-Toddler Meaningful Auditory Integration Scale (IT-MAIS) have been used to measure auditory skill development in deaf infants with CIs (12). However, such measures can only assess auditory skills that are observable in natural situations. They do not assess whether infants can discriminate particular phonetic contrasts. Furthermore, such measures lack appropriate norms for normal hearing (NH) or deaf infants and might easily be confounded by parental and caregiver bias. Therefore it is difficult to determine the value of these measures for determining what skills are truly being developed in deaf infants who use a CI.

One possible solution is to measure the spontaneous vocal behaviours that infants produce. A group of researchers has studied early vocalizations and babbling of deaf infants with CIs. Schauwers et al. recently observed deaf infants and recorded their vocalizations before and after CI (13). They found that, although the onset of canonical babbling (infant vocalizations consisting of consonant-vowel repetitions) was delayed in these infants compared to NH infants, all infants began to babble within 1–4 months after receiving their device. Sharma et al. reported a similar maturation in babbling behaviour in deaf infants following implantation and found that it correlated with maturation in the central auditory evoked potential (14). These studies have provided preliminary evidence that measurement of pre-linguistic vocal behaviour such as babbling can be used to measure benefit from a CI.

However, direct measures of infant babbling require hours of recording and many more hours in sequencing, transcribing, and analyzing the video content. Furthermore, these studies are observational and cannot easily be incorporated into a controlled experiment. In contrast, techniques that rely on measuring elicited infant behaviours, such as eye-gaze or head-turning, in response to carefully manipulated stimuli may be more promising. Such behaviours can be easily and quickly measured, and are known to vary predictably with the arousal state of the infant and change measurably with shifts in attention (15).

One eye-gazing paradigm that has previously been used by developmental scientists to study speech discrimination skills in NH infants is the visual habituation procedure (VH). The VH has been used to test infants' ability to discriminate native and non-native phonetic contrasts (16,17). This procedure exploits the fact that infants tend to orient longer to a visual display when listening to a novel auditory stimulus than when listening to an auditory stimulus that they have heard many times before. Infants sit on the caregiver's lap in a sound booth and are presented with several trials of a visual display paired with a repeating sound until their looking time to the display decreases to reach a 'habituation' criterion. They are then presented with the same visual display paired with a novel sound. An increase in looking time in response to the novel sound/visual stimulus pair is taken as evidence that the habituated and novel auditory stimuli were discriminated. The VH is easily adaptable to many different speech or non-speech contrasts and has a relatively low attrition rate compared to other infant protocols (18).

Houston et al. successfully adapted the VH to assess discrimination skills in deaf infants who use CIs (19). Infants were tested on their ability to discriminate repetitions of a continuous "ahhhh" sound versus repetitions of a discontinuous pattern ("hop hop hop ...") at various intervals before and after CI. Normal hearing infants looked significantly longer at a checkerboard pattern when paired with either repeating speech sound than when presented in silence. This preference for speech over silence was not seen in the pre- or post-implant CI infants. Nevertheless, infants who had used their CI for six months, like their NH counterparts, looked longer at a checkerboard pattern, on average, when it was paired with the novel speech stimulus. These data suggested that deaf infants, even after CI, do not show the same attention to speech versus silence seen with NH infants, although deaf infants were able to discriminate basic continuous and discontinuous speech patterns by six months post-implant (19).

In order to make the VH procedure more robust and sensitive to detect discrimination capacity, Houston et al. modified the original protocol in three important ways (20). First, rather than presenting only one novel and one 'old' (containing the habituated word) trial after habituation, infants were presented with 14 test trials. This enabled more data points to be collected from an individual infant to increase statistical power to detect group and individual effects. Secondly, the authors employed alternating (old novel old novel ...) versus non-alternating (old old old ...) trials during the test phase rather than simply using old versus novel trials. Use of alternating trials was based on the work of Best and Jones (1998) who have reported that infants show strong looking preferences for alternating speech sounds compared to non-alternating speech sounds. Finally, Houston et al. made alternating trials less frequent than non-alternating trials during the test phase. This was based on electrophysiological methodologies that exploit the perceptual saliency of infrequent stimuli (21). The resulting protocol, termed the VH-hybrid procedure, proved to be more robust and sensitive than the original VH in detecting discrimination of non-words in NH nine-month-olds (20).

The first aim of the present study was to expand the findings of Houston et al. (2003), using a different speech contrast – non-word discrimination. The non-words, *seepug* and *boodup*, had the same rhythmic structure so that infants would not be able to use pattern perception to detect differences as in the earlier study. Instead, the non-words differed with respect to their segmental phonological information. We hypothesized that deaf infants would not show discrimination of non-words prior to implantation, but if they could perceive spectral information from their CIs they would show evidence of discrimination after implantation. Effects of age at implantation, length of CI use, and pre-operative hearing on non-word discrimination skills were also investigated.

A second aim of the present study was to replicate the earlier finding that CI infants, in contrast to NH infants, did not show a looking-time preference for speech trials. In contrast to the earlier study, in which the non-speech trials were visual-only, we used audiovisual non-speech trials to compare to the audiovisual speech trials. We hypothesized that NH infants would show a looking preference for speech trials whereas CI infants would not.

Patients and methods

Subjects

Infants were recruited during the pre-implant assessment in a large university hospital-based CI program. Inclusion criteria were: bilateral hearing loss to a degree consistent with audiological candidacy for a CI (22) and planned implantation prior to two years of age. The infants were then enrolled in a longitudinal testing protocol in which they were tested at various intervals from pre-implantation to three months post-implantation. Each testing session was conducted on a day in which multiple other clinical appointments were scheduled including audiological and otolaryngological examinations, CI mapping sessions, and speech therapy. In addition, several other concurrent behavioural research studies of speech perception, word learning, and related skills competed for each infant's time during the busy day. Therefore, the interval at which infants could be tested varied depending on scheduling issues, time constraints, and parental availability. A total of eight testing sessions were excluded from the analyses due to failure to complete the protocol, or experimental error in set-up of the experiment. The most common reason for non-completion was crying ($n = 6$), with another too restless and another vomiting.

Eleven CI infants completed testing during the pre-implant interval. Five of these 11 infants also completed testing during the post-implant intervals from two weeks to three months post-implantation. An additional five infants, who were not tested prior to implantation, were tested post-implant for a total of 10 post-implant infants. Five of the 10 post-implant infants completed testing at more than one post-implant interval and their individual data were averaged across testing sessions.

For comparison purposes, we recruited a total of 10 NH infants who were chronologically age-matched to the overall sample of CI infants. Per caregiver report, each infant passed newborn hearing screening in both ears and had no known hearing loss or delay in speech and language development. For any infant with three or more prior ear infections, criteria for inclusion were bilateral present otoacoustic emissions and type A tympanograms. Any infant with current ear infection was rescheduled. The mean age of the NH sample was 17.0 (SD = 4.8) months compared to 14.6 (SD = 6.5) months for the pre-implant CI group and 17.0 (SD = 4.6) months for the post-implant CI group. None of these mean ages was significantly different from one another in independent sample *t*-tests ($p > 0.05$). Pre-implant CI infants tended to have lower pre-implant aided pure-tone thresholds than post-implant CI infants but this difference was not significant ($p > 0.05$). The demographic data are shown in Table I.

Apparatus

The testing was conducted in a custom-designed double-walled IAC sound booth. Infants sat on their caregivers' laps approximately 5′ in front of a 55″ wide-aspect television (TV) monitor. The visual stimuli were displayed in the center of the TV monitor, at approximately eye level to the infants. The auditory stimuli were presented through both the left and right loudspeakers of the TV monitor. The experimenter observed the infants from a separate room via a hidden, closed-circuit digital camera and controlled the experiment using the Habit software package (23) running on a Macintosh® G5 desktop computer.

Stimuli

Stimuli were constructed of two highly contrastive naturally produced audiovisual non-words: *boodup* and *seepug*. Both non-words have the same rhythmic structure and conform to the predominant strong/weak stress pattern in English (24), so they are likely to be heard as possible words by English-learning infants (25). Five tokens of *seepug* and five tokens of *boodup* were selected from 50 video recordings of a female talker who was instructed to look into the camera and produce the non-words as if she were speaking to an infant.

The video recordings were edited using FinalCut Pro HD 4.5 (Apple Computer). Each token was edited so that the face was centered and the sound level was equivalent across tokens (65 + 5dB SPL). From each token, a QuickTime (Apple Computer) movie file was created, which consisted of 17 repetitions of that token. Within the movie files, each repetition was edited so it appeared to fade in and fade out, in order to smooth out the transition from one repetition to another. The duration of the video part of each token was 1.83 s. The duration of the auditory portion of the *seepug* and *boodup* tokens from the beginning of the first vowel varied from 0.62 s to 0.72 s.

Four of the *seepug* tokens (*seepug* 1–4) or four of the *boodup* tokens (*boodup* 1–4) were used during the habituation phase of the experiment. Each habituation trial consisted of repetitions of one of the four tokens. An additional 'fifth' token of each non-word was used during the test phase (*seepug* 5, *boodup* 5). Multiple habituation tokens were used to promote more robust, generalized, representations of the non-word and to prevent infants showing a novelty preference based solely on non-linguistic differences between habituated and novel tokens (such as differences in facial expression or vocal inflection). For the test phase, two types of trials were constructed: 'alternating' (A) trials and 'non-alternating' (NA) trials. For the NA trials, two tokens of the habituated non-words were presented in alternating order (i.e. *seepug* 1 and *seepug* 5). For the A trials, *seepug* 5 and *boodup* 5 were presented in alternating order. The interstimulus intervals (ISI) between tokens were identical across both trial types. The reason for having two tokens for the NA trial was that there was stimulus alternation in both conditions – token variation for the NA trials and categorical variation for the A trials. This ensures

Table I. Demographic characteristics of the three groups.

	Age at implant	Age at test	Baseline PTA	Length of CI use
Pre-implant CI	N.A.	14.6 (SD = 6.5) 6.0–22.7	76.8 (12.3) 53–90	N.A.
Post-implant CI	15.6 (SD = 4.51) 10.2–22.7	17.0 (SD = 4.6) 11.2–24.3	84.6 (10.1) 60–90	1.4 (SD = 1.0) 0.03–3.4
NH	N.A.	17.0 (SD = 4.8) 11.3–24.3	N.A.	N.A.

Note: All values given in months with exception of pre-implant binaural aided PTA that is in dB HL. Mean values are given followed by standard deviations in parentheses followed by the high and low values for each group. N.A.: not applicable.

that a looking-time preference for the A trials would not be simply due to alternations in non-linguistic acoustic information.

Two additional stimuli were used in the experiment. A silent video of an infant smiling was used as the 'attention getter' before each trial, as described below. A computer-graphic animation, consisting of geometric shapes that moved back-and-forth accompanied by a continuous, periodic auditory stream was presented at the beginning and end of the experiment. Looking-time to these audiovisual non-speech trials was measured for comparison to the audiovisual speech trials used throughout the rest of the experiment.

Procedure

Infants' looking times to the videos were assessed during the experiment session using the Habit software program (23). The experimenter sat in a control booth located outside the experimental booth and observed the infants on a TV monitor which had a closed-circuit connection with a hidden video camera in the experiment booth. The experimenter was blind to which stimulus was being presented on each trial and simply pushed a button on the computer keyboard whenever the infants' eyes were oriented toward the video on the TV monitor. Likewise, the caregiver who held the infant in the booth listened to loud masking music over sound-attenuating enclosed headphones (Peltor Aviation Headset 7050), and so was also blind to the stimulus conditions. Before the onset of each trial, the infant's attention was brought to the monitor by presenting the 'attention getter'. Once the infant oriented to the TV, the trial was initiated by the experimenter and continued until the infant looked away from the video for one second or more or until the maximum trial length of 30 s. If an infant looked away and then back to the stimulus for less than one second, the trial continued. The infant's total looking time for each trial was calculated. Immediately before and after the experiment, infants were presented with a stimulus (described above) that was completely unrelated to the experiment stimuli.

The main experiment consisted of two phases, as illustrated in Figure 1. During the habituation phase, infants were presented with repetitions of four *seepug* or four *boodup* tokens. Each trial consisted of repetitions of a single token. The trials were ordered so that each of the four tokens occurred once in every set of four trials and no token was repeated across two consecutive trials. The habituation phase continued until the infant's mean looking time over three consecutive trials was 50% or less than the mean looking time during the first three trials. When this criterion was met (or if 15 habituation trials had elapsed), the test phase began. The test phase consisted of 14 trials – usually 10 A trials and 4 NA trials[1]. For the first two test trials, one was an A trial and one was an NA trial with the order counterbalanced across infants. The ordering of the last 12 test trials was pseudorandom with the caveat that no two consecutive trials could be A trials.

Results

We hypothesized that if infants could discriminate the two non-words, they would demonstrate longer looking times to the A trials compared to the NA trials. Mean looking times during the test-phase trials as a function of 'group' (pre-implant CI, post-implant CI, NH) and 'trial type' (NA or A trial) are shown in Figure 2. For NH infants, mean looking time for NA trials was 12.8 s (SD = 7.0) compared to 19.9 s (SD = 8.6) for A trials. For pre-implant CI infants (pre-CI), mean looking times were 7.6 s (SD = 4.6) and 7.5 s (SD = 3.6) for NA trials and A trials, respectively. For post-implant CI infants (post-CI), mean looking times were 9.0 s (SD = 4.0) and 9.4 s (SD = 4.9) for NA and A trials, respectively. These mean data were then subjected to a repeated-measures ANOVA with group as the between-subjects variable and trial type as the within-subjects variable. Post-hoc tests were then conducted as appropriate.

A significant main effect of trial type was found – $F(1.28) = 15.50$, $p < 0.0001$ – indicating that infants looked longer during A than during NA trials across

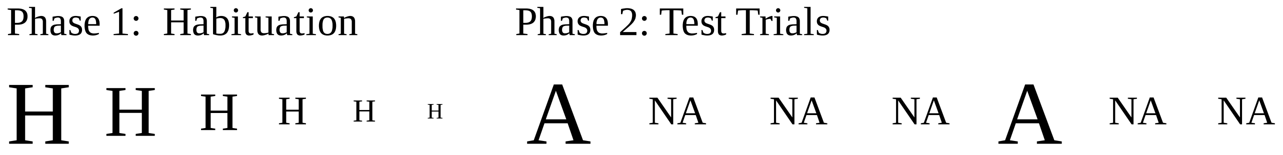

Figure 1. VH procedure. Trial type is represented by letters: 'H' for habituation trials, A for alternating trials, NA for non-alternating trials. Looking time is represented by letter size: smaller letters, shorter looking times. During habituation infants were presented with consecutive trials of the repeating nonsense word *seepug* until looking time decreased to a set criteria. During the test phase, infants were presented pseudo-randomly with A trials and NA trials. Longer looking time during A trials was taken as evidence of discrimination of *seepug* and *boodup*.

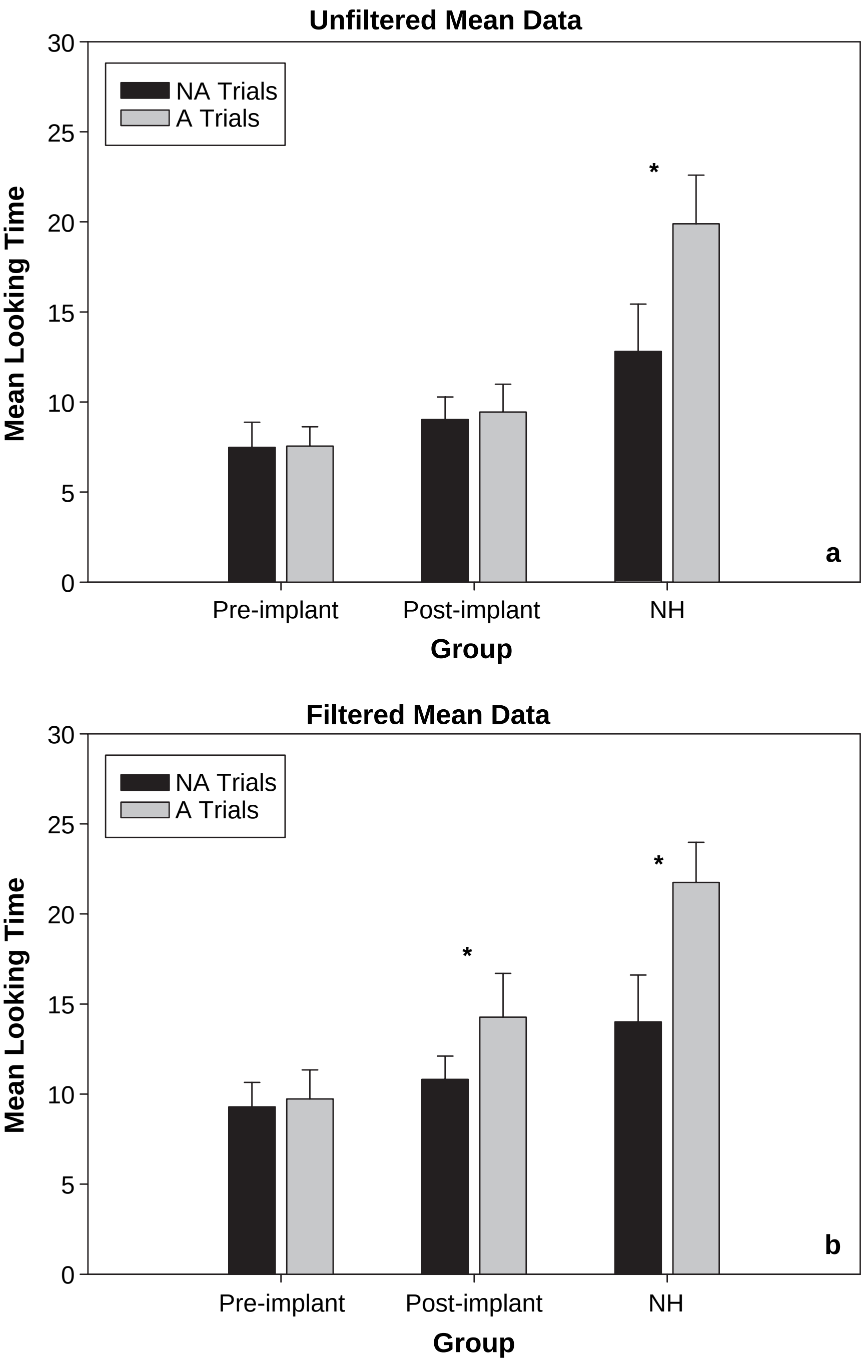

Figure 2. Mean looking time as a function of trial type and group. Means for all data (unfiltered) are shown in 2a and means for data with <3 s trials removed (filtered) are shown in 2b. Dark bars represent NA trial means and light bars represent A trial means. Error bars reflect standard error of the mean. Asterisks indicate a significant difference between mean NA and A trial looking times for a given group based on paired *t*-tests.

groups. A main effect of group was found as well – $F(2.28) = 6.989$, $p = 0.003$. Bonferroni post-hoc tests showed that NH infants had significantly longer looking times across test trials than pre-CI infants ($t = 8.83$, $p = 0.004$), as well as post-CI infants ($t = 7.11$, $p = 0.027$). The difference in mean looking times across test trials between pre-CI and post-CI groups did not reach significance ($t = 1.72$, $p > 0.05$). In addition to the above main effects, a significant interaction was found between group and trial type – $F(2.28) = 13.31$, $p < 0.0001$. Paired *t*-tests (one-tailed) were then conducted for each group individually with the variable trial type as the independent variable and looking time as the dependent variable. These results show that NH infants showed a significant visual preference for A over NA trials (t $(9) = 6.289$, $p < 0.0001$). In contrast, neither pre-CI nor post-CI infants demonstrated a significant visual preference for A over NA trials ($t(10) = -0.071$, $p = 0.473$) ($t\ (9) = 0.362$, $p = 0.363$), respectively.

The mean looking times for each group at different phases of the protocol are illustrated in Figure 3. The first and last phase, pre-test and post-test, included trials with a repeating audiovisual non-speech stimulus described previously. In the middle two phases, habituation and test, all stimuli were audiovisual speech trials. A repeated measures ANOVA was conducted with 'group' as the between-subjects variable and 'phase' as the within-subjects variable. Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(5) = 27.85$, $p = .0001$) for phase. Huynh-Feldt's estimate of sphericity ($\varepsilon = .85$) was used to correct degrees of freedom. The main effect of group was not significant, $F(2.28) = 0.366$, $p = 0.697$, indicating that, across all phases, NH and both groups of CI infants looked for similar amounts of time across all phases. A main effect of 'phase' was found – $F(2.55, 71.27) = 5.774$, $p = 0.002$ – and also the phaseXgroup interaction was significant – $F(5.09, 71.27) = 2.384$, $p = 0.046$.

To analyze the phaseXgroup interaction, a one-way ANOVA was conducted for each test phase with 'group' as the independent variable. For the pre-test and post-test trial, both of which consisted of a non-speech stimulus, no significant effect of group was found – $F(2.28) = 0.271$, $p = 0.765$ and $F(2.28) = 0.187$, $p = 0.831$, respectively. In contrast, a significant effect of group was found for mean looking time during habituation trials – $F(2.28) = 6.341$, $p = 0.005$. A significant effect of group was also found for mean looking time during test trials – $F(2.28) = 6.989$, $p = 0.003$. Post-hoc Bonferroni tests were then carried out to elucidate the main effects[2]. For the habituation trials, NH infants looked significantly longer than both pre-CI ($t = 6.39$, $p = 0.007$) as well as post-CI ($t = 5.50$, $p = 0.028$) infants.

The reduced test-phase looking times of pre- and post-CI infants relative to NH infants may have limited our ability to detect non-word discrimination in the former groups. Upon close inspection of the raw data it became apparent that a number of the infants showed looking times on individual test trials as low as 1–2 s in duration. Such short looking times could not afford infants the opportunity to react to the novel tokens because the novel tokens always occurred as the second token of each A trial and began more than 2.5 s into the trials. Thus, infants would need to orient to the stimuli for approximately 3 s in order to be exposed to and have time to engage their attention to the novel tokens. The incidence of these <3 s trials was much greater for CI infants than for NH infants. Therefore, the significant interaction between group and trial type described earlier may have been due to an overall effect of attention rather than to actual perceptual differences between NH and CI infants. In other words, CI infants' shorter looking times may have resulted in

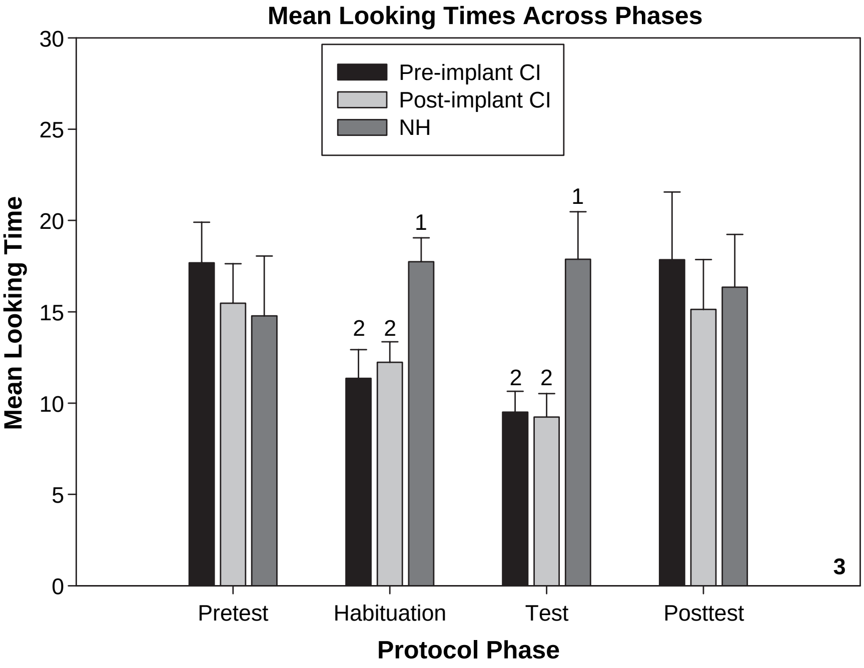

Figure 3. Mean looking time as a function of VH phase and group. These means are derived from unadjusted data (trials <3 s included). Dark bars represent pre-CI means, light bars represent post-CI means, and medium bars represent NH means. Error bars reflect standard error of the mean. Numbers indicate significant differences between individual groups (1 s significantly different from 2 s).

fewer opportunities to be exposed to and respond to the novel stimulus.

In order to test the possibility that the lack of a trial type effect in CI infants was due to not having an opportunity to hear the novel non-words, we reanalyzed the data eliminating all trials where the looking time was less than 3 s. We hypothesized that post-CI infants would be more likely to demonstrate discrimination if we analyzed only trials in which they had sufficient time to hear the novel token at least once. Two of the post-CI infant testing sessions had to be excluded completely from the subsequent analyses after these trials were removed due to the fact that no A trials remained. However, both of these infants were among those who completed the testing at multiple intervals. Therefore, the final sample size remained identical in the adjusted data.

A 2×3 repeated measures ANOVA was then performed using the adjusted data. Again, a significant main effect of trial type was found – $F(1.28) = 24.44$, $p < 0.0001$ – indicating that infants looked longer during A than during NA trials across groups when trials <3 s were removed. The main effect of group remained significant as well – $F(2.28) = 5.351$, $p = 0.011$. Bonferroni post-hoc tests showed that NH infants had significantly longer looking times across test trials than pre-CI infants ($t = 8.36$, $p = 0.009$). However, with the <3 s test trials removed, looking times of NH infants and post-CI infants across test trials were not significantly different ($t = 5.33$, $p = 0.159$). Again, the difference in mean looking times across test trials between pre-CI and post-CI groups did not reach significance.

A significant interaction was found again between group and trial type – $F(2.28) = 7.41$, $p = 0.003$. As shown in Figure 2b, this interaction was different in nature when the short <3 s trials were removed. The main difference was that post-CI infants looked significantly longer during A trials than during NA trials (paired t (9) = 1.95, one-tailed $p < 0.042$). The looking preference for A trials remained significant for NH infants and remained not significant for the pre-CI infants (t (10) = 0.380, one-tailed $p = 0.356$).

The following analyses were then conducted using the adjusted data for the post-CI infants. In order to test for effects of hearing status, age at implantation, and length of CI use on non-word discrimination, we divided the post-CI group into one of two subgroups. In the 'discrimination' group, we included five children with A-NA trial looking time difference scores of 2.86 s, 3.83 s, 5.23 s, 12.82 s, and 13.25 s. The mean difference score of the 'discrimination' group was 7.60 s (SD = 5.04). In the 'non-discrimination' group the five infants had looking-time difference scores of −2.86 s, −1.67 s, −0.79 s, 0.8 s, 1.19 s. The mean difference score of the 'non-discrimination' group was −0.67 s (SD = 1.69). A series of independent samples t-tests was then conducted with group (discrimination vs. non-discrimination) as the independent variable and age at test, age at implantation, length of CI use, and pure-tone average (unaided) as the dependent variables. Table II shows the means for each dependent variable as a function of group. We found no significant effect of discrimination group on any of the four variables.

Discussion

The goal of cochlear implantation in infancy is to enable profoundly deaf patients to begin to develop spoken language skills as early as possible. However, it is often up to three years of age before children can complete traditional behavioral tests of speech perception and language. Without objective testing protocols for infants with CIs, their progress in acquiring spoken language skills cannot be measured objectively until they are in toddler-hood or early childhood. One of the major goals of this paper is to show that the VH-hybrid procedure can be used to measure speech discrimination capacity during a period when infants typically develop important speech perception skills (27). As a result, the degree of benefit from a CI may be able to be assessed in the first two years of life.

This study provides additional evidence that deaf infants can discriminate speech sounds soon after

Table II. Post-implant CI infant characteristics as a function of non-word discrimination.

	Group		
	Non-discrimination	Discrimination	t-test (df = 8)
Age at implantation	14.2 (SD = 4.9)	16.9 (SD = 4.2)	−0.97, $p = 0.362$
Age at test	16.0 (SD = 4.7)	17.9 (SD = 4.4)	−0.647, $p = 0.536$
Length of CI use	1.9 (SD = 1.4)	1.0 (SD = 0.6)	1.30, $p = 0.230$
Aided pure tone average	88.6 (SD = 1.3)	80.6 (SD = 13.7)	1.30, $p = 0.239$

Note: All values given in months with exception of aided pure tone average that is in dB HL. Mean values are given followed by standard deviations in parentheses followed by the high and low values for each group.

implantation (19) and, to our knowledge, provides the first evidence of CI infants' discrimination of speech sounds that differ on spectral rather than rhythmic and intonational properties. The use of natural audiovisual recordings of a speaker producing the non-words in an infant directed manner probably made the task easier for infants to accomplish than an auditory-only task because they could use visual information (28). Studies of older prelingually deaf children with CIs have demonstrated gains in speech perception scores when presented in audiovisual, compared with auditory only, format (29,30). Blending illusions such as the McGurk effect, have been demonstrated in normal hearing infants as evidence for the capacity to integrate auditory and visual linguistic information from an early age (31). Thus, an important limitation of the present study is that we could not determine whether the non-word discrimination shown by post-implant CI infants was due to auditory, visual, or a combination of skills. Future studies with unimodal stimuli are needed to address this question.

When looking at all the data from the test-phase trials, only NH infants showed evidence of discrimination of *seepug* and *boodup*. However, when we examined overall looking times during the VH-hybrid procedure we found that NH infants looked longer than both groups of CI infants during all trials containing speech stimuli. Interestingly, there were no differences between groups for looking times during the pre- and post-test trials (both of which were non-speech stimuli). These results show that CI infants do not show the same degree of visual interest to speech trials. This cannot be due to NH infants' familiarity with the stimuli as non-words were used (primarily for this reason).

One reason for the difference in speech trial looking times between NH and CI infants could be auditory experience. The CI infants are relatively deprived of meaningful auditory input until they receive their device. In contrast, NH infants have been fully immersed in a speech-rich environment. It is possible that NH infants' attention to speech in general is more pronounced than CI infants who may need some amount of experience with auditory input before it becomes an integral part of how they interact with their environment. This is an important area of future research if we are to better understand differences in looking behaviour between CI and NH infants.

Close inspection of the raw data showed that CI infants (and less so NH infants) looking times for some test trials were too short to hear and attend to the novel token in the A trials. When these <3 s trials were removed from all three groups' data, our analyses showed that NH infants and post-CI infants both discriminated *seepug* and *boodup*. Pre-CI infants still did not show evidence of non-word discrimination. These removed data suggest that shortly after implantation, within three months of CI use, PLD infants can discriminate audiovisually presented non-words.

We did not find evidence of an effect at implantation on non-word discrimination. However, our sample size was small – only 10 participants in the post-CI group. As previously mentioned, other studies of speech perception in older children with CIs have found that earlier implanted children show higher speech perception scores (9–11). Further testing with a larger sample of implanted infants may reveal such an effect. We also did not find an effect of age at test, length of CI use, or pre-operative aided PTA on non-word discrimination.

The VH hybrid procedure was developed not only to test discrimination skills of groups of infants, but also to test discrimination skills of individual infants (20). With multiple A and NA trials in the test phase, Houston et al. were able to use single-subject statistical techniques to measure a looking preference in eight of 10 NH nine-month-old infants (20). We did not conduct the single-subject analyses in the present paper due to the high incidence of <3 s looking time trials in CI infants. With these trials excluded, there were not enough A and NA trials for each subject to test individual infant discrimination. In future testing with the VH hybrid procedure, we plan to modify the A trials so that the novel token is presented first (novel old novel old . . .). With this modification, we hope to increase overall looking times and to decrease the incidence of <3 s trials.

Thus, it is possible that such further modifications to the VH-hybrid procedure will enable us to detect speech discrimination in an individual infant. The clinical importance of this goal cannot be overstated. The VH hybrid may prove useful not only as an instrument to test for general developmental trends in a population, but also as a tool to study individual differences in speech discrimination capacity. Such a tool would enable earlier characterization of the speech perception skills of infants with CIs as well as aid in identification of infants who are struggling to develop such crucial skills. Furthermore, the VH hybrid could help to elucidate which types of phonetic contrasts (i.e. voicing) are most difficult for individual infants with CIs and lead to more individualized habilitation of these infants.

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Notes

1. In an earlier version of the protocol, seven A and seven NA trials were presented in alternating order. Two of the pre-implant and two of the post-implant sessions were conducted in this way. Testing with normal-hearing infants later showed that making the A trials less frequent made the visual preference for A vs. NA trials more robust (20) Houston D, Horn D, Qi R, Ting J, Gao S. Assessing Speech Discrimination in Individual Infants. Infancy. 2007;12: In press.
2. To prevent redundancy, the post-hoc tests for looking times during the test phase are excluded here as they essentially mirror the results of the repeated measures ANOVA described earlier.

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