Auditory Discrimination of Lexical Stress Patterns in Hearing-Impaired Infants with Cochlear Implants Compared with Normal Hearing: Influence of Acoustic Cues and Listening Experience to the Ambient Language

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Objectives: To assess discrimination of lexical stress pattern in infants with cochlear implant (CI) compared with infants with normal hearing (NH). While criteria for cochlear implantation have expanded to infants as young as 6 months, little is known regarding infants' processing of suprasegmental-prosodic cues which are known to be important for the first stages of language acquisition. Lexical stress is an example of such a cue, which, in hearing infants, has been shown to assist in segmenting words from fluent speech and in distinguishing between words that differ only the stress pattern. To date, however, there are no data on the ability of infants with CIs to perceive lexical stress. Such information will provide insight to the speech characteristics that are available to these infants in their first steps of language acquisition. This is of particular interest given the known limitations that the CI device has in transmitting speech information that is mediated by changes in fundamental frequency.

Design: Two groups of infants participated in this study. The first group included 20 profoundly hearing-impaired infants with CI, 12 to 33 months old, implanted under the age of 2.5 years (median age of implantation = 14.5 months), with 1 to 6 months of CI use (mean = 2.7 months) and no known additional problems. The second group of infants included 48 NH infants, 11 to 14 months old with normal development and no known risk factors for developmental delays. Infants were tested on their ability to discriminate between nonsense words that differed on their stress pattern only (/*dóti*/ versus /*dotí*/ and /*dotí*/ versus /*dóti*/) using the visual habituation procedure. The measure for discrimination was the change in looking time between the last habituation trial (e.g., /*dóti*/) and the novel trial (e.g., /*dotí*/).

Results: (1) Infants with CI showed discrimination between lexical stress pattern with only limited auditory experience with their implant device, (2) discrimination of stress patterns in infants with CI was reduced compared with that of infants with NH, (3) both groups showed directional asymmetry in discrimination, that is, increased discrimination from the uncommon to the common stress pattern in Hebrew (/*dóti*/ versus /*dotí*/) compared with the reversed condition.

Conclusions: The CI device transmitted sufficient acoustic information (amplitude, duration, and fundamental frequency) to allow discrimination between stress patterns in young hearing-impaired infants with CI. The present pattern of results is in support of a discrimination model in which both auditory capabilities and "top–down" interactions are involved. That is, the CI infants detected changes between stressed and unstressed syllables after which they developed a bias for the more common *weak–strong* stress pattern in Hebrew. The latter suggests that infants with CI were able to extract the statistical distribution of stress patterns by listening to the ambient language even after limited auditory experience with the CI device. To conclude, in relation to processing of lexical stress patterns, infants with CI followed similar developmental milestones as hearing infants thus establishing important prerequisites for early language acquisition.

Key words: Development of auditory skills, Infants with cochlear implants, Language acquisition, Lexical stress patterns.

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INTRODUCTION

Cochlear implantation in infancy is important for stimulating the developing brain and for providing optimal opportunities for the acquisition of spoken language (e.g., Papsin & Gordon 2007; Kral & O'Donoghue 2010). Because the infant is a novice listener, it initially treats speech as a continuous stream of nonmeaningful sounds with no reliable pauses between words and no single systematic acoustic marking of word boundaries. Exposure to the ambient language and to child-directed speech of their caregivers allow infants to track the statistical distribution of segmental and suprasegmental sound patterns in their language and to regularize them at various levels of linguistic analyses (e.g., Thiessen & Saffran 2007). While such information is available for normal-hearing (NH) infants, there are limited data for hearing-impaired infants with cochlear implant (CI) at their initial stages of device use.

To date, studies have shown that infants with CI preferred speech of their ambient language over nonspeech sounds (Segal & Kishon-Rabin 2011) and over an unfamiliar language as early as a few months following cochlear implantation (Kishon-Rabin et al. 2010). They were also able to discriminate segmental changes both for isolated vowels and for words (Houston et al. 2003; Barker & Tomblin 2005; Horn et al. 2007). Yet, the perception of suprasegmental information has received very little attention in this population despite the fact that it plays an important role in early language acquisition and has been studied extensively in normal developing infants (e.g., Spring & Dale 1977; Jusczyk et al. 1999; Thiessen & Saffran 2007; Skoruppa et al. 2009).

Lexical stress pattern, which refers to the common position of stress in words of a specific language, is an example of suprasegmental information that is known to assist infants in early stages of language acquisition (e.g., Jusczyk et al. 1999; Thiessen & Saffran 2007). Lexical stress (e.g., pérmit versus permít) is acoustically marked by changes in fundamental frequency

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(F0), amplitude, duration, or a combination thereof which create a perceptual impression that one syllable in the word is more prominent (i.e., stressed) than others (Fry 1958; Lehiste 1970). The common position of stress in the word (i.e., lexical stress pattern) is unique to each language. In English, for example, the first syllable in a bisyllabic word is often stressed (Hayes 1995), whereas in Hebrew, the second syllable is commonly stressed (Segal et al. 2009).

Studies in hearing newborns (Sansavini et al. 1997; Van Ooijen et al. 1997) and young infants (Spring & Dale 1977; Jusczyk & Thompson 1978) found that NH infants are able to perceive changes in lexical stress very early in development. By the second half of the first year of life, NH infants are also able to exploit stressed syllables for segmenting words from fluent speech (e.g., Jusczyk et al. 1993, 1999; Curtin et al. 2005; Nazzi et al. 2005; Thiessen & Saffran 2007; Polka & Sundara 2011). Semitic languages, such as Hebrew, possess a rich morphology that is overtly marked in many cases by the addition of a stressed syllable (e.g., *madáf* "shelf" singular versus ma*dafím* "shelves" plurals, Graf & Ussishkin 2003). Thus, in Semitic languages, stress-pattern discrimination allows infants to detect the morphological structure of the language.

Despite the importance of stress perception for language acquisition, there is no study to our knowledge that investigated the ability of infants with CI to discriminate between stress patterns. Additional interest in this issue stems from the fact that not all the cues for lexical stress, in particular changes in intensity and fundamental frequency, are readily transmitted by the CI device (e.g., Au 2003; Barry et al. 2002; Ciocca et al. 2002; Wei et al. 2004; Peng et al. 2009; Zhang et al. 2010; Most et al. 2012). Although early studies showed smaller difference limens (DL) for intensity for electrical than for acoustic stimulation (e.g., Shannon 1983; Zeng 2004), this CI advantage has been offset by the small dynamic range of most CI users (approximately 10 to 30 dB compared with approximately 120 dB in NH, Zeng & Shannon 1999). This has resulted in reduced number of discriminable steps, 7 to 45 in CI users compared with 50 to 200 in NH (Nelson et al. 1996). When CI listeners were tested under more natural listening conditions such as in free field and with their clinical speech processor (as opposed to direct stimulation of single electrodes), they were found to perform poorer than NH by a factor of 2.4 (Rogers et al. 2006). Similarly, CI users showed greater DL for frequency than NH [e.g., DL of 4 of 13% in CI users (Geurts & Wouters 2001) compared with less than 0.5% in NH listeners (e.g., Moore & Glasberg 1990; Kishon-Rabin et al. 2001)]. This poor performance of the CI users has been attributed primarily to poor place pitch cues determined by the limited spectral presentation in the CI electrode array, leading to a DL for frequency greater than one octave (Laneau et al. 2004; Rogers et al. 2006). While this DL for frequency was found to be good enough for CI users to distinguish between male and female voices (Fuller et al. 2014), it was not sufficient for detecting more subtle changes in patterns of intonation (e.g., Chatterjee & Peng 2008; Luo et al. 2012).

In the presence of spectrally reduced speech, CI users are assumed to rely on periodicity cues transmitted to individual electrodes via the temporal envelope (e.g., Shannon 1983; Zeng 2002; Chatterjee & Peng 2008). It was further suggested that the transmission of such temporal information is dependent on the rate of stimulation (e.g., Javel 1990). Specifically, higher stimulation rate resulted in better pitch discrimination performance for some CI users (e.g., McKay et al. 2000; Au 2003) but not for others (e.g., Barry et al. 2002). Although the addition of temporal pitch cues to the place-pitch cues resulted in improved pitch discrimination and better perception of the direction of pitch change in CI users compared with place-pitch cues only (e.g., Laneau et al. 2004; Lou et al. 2012), performance remained poorer than NH. In addition to the fact that CI users have generally a smaller number of stimulable auditory nerve fibers of the impaired auditory system and a relatively small number of available perceptual channels (Javel 1990), the insufficient transmission of periodicity cues may also be related to the limited transmission of the fine temporal information in the speech envelope, especially in the less advanced CI processors (e.g., Laneau et al. 2004; Gfeller et al. 2007), the saturation of temporal pitch perception for CI users at around 300 Hz (e.g., Zeng 2002) thus limiting the amplitude modulation frequency of the temporal envelope of the incoming signal (which are superimposed on fixed train pulse trains) to 300 Hz (e.g., Luo et al. 2012), and the inconsistency of the CI device in transmitting temporal information at the correct tonotopic location (e.g., Luo et al. 2012). Moreover, the difficulty of CI users to perceive changes in pitch is further aggravated when listening occurs in noisy conditions (e.g., Qin & Oxenham 2003). Considering infants normally acquire speech and language in natural non-noise-free environments, the question whether infants with CI develop the ability to perceive and differentiate between basic linguistic patterns such as those related to lexical stress has important implications for understanding the early processes of language acquisition in relation to the limitations imposed by their impaired auditory system and those of the CI device.

Thus, purpose of the present study was to determine whether infants with only few months of CI use were able to discriminate between lexical stress patterns and to compare this ability to a control group of NH infants. An additional purpose was to determine whether there is symmetry in discrimination between segments of lexical stress pattern as a function of order of presentation. Some studies of the development of lexical stress in NH infants reported asymmetry in discrimination between lexical stress patterns (also termed directional asymmetry). Specifically, stronger discrimination was found when a change was *to* the common stress pattern of the language than when a change was *from* it (e.g., Weber et al. 2004, 2005; Friederici et al. 2007). If in the present study, infants with NH and CI show a similar directional asymmetry for discrimination of lexical stress patterns, it may support the influence of listening experience and exposure to the statistical distribution of stress patterns in the ambient language (i.e., top–down processing). This will provide important insight to the trajectory of development of speech processing in infants with CI.

MATERIALS AND METHODS

Participants

Twenty-six infants with CI and 68 NH infants were recruited for the study. Of the infants with CI, 6 (23%) were excluded because of crying (3) and restlessness (3). Of the NH infants, 20 (29.4%) were excluded due to crying (3), restlessness (17), and lack of habituation (1). Eventually, the study included 20 infants with profound bilateral sensorineural hearing loss with CI (mean age = 18;17, SD = 7; 4 [months; days]) who used their CI device between 1 and 6 months (mean = 2.65, median = 2, SD = 1.79)

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and 48 NH infants (mean age =12;14, SD = 1;23). Background information for the infants with CI is shown in Table 1. It can be seen that for 18 of the 20 infants with CI, hearing loss was identified during newborn hearing screening and for 3 infants, identification was at 8 to 10 months after meningitis. All infants were full term at birth with an APGAR (activity, pulse, grimace, appearance, respiration) score of 9 to 10. No additional neurological, anatomical, and/or physiological abnormalities were reported via parental questionnaire. All infants were fitted with hearing aids 3 to 6 months after the identification of hearing loss and participated in an aural habilitation program. Mean age at cochlear implantation was 15.9 months (median = 14.5, range = 10.1 to 28 months, SD = 5.4). Infants used either a Nucleus (n = 12) or a Medel device (n =10). Inclusion criteria were cochlear implantation before 2.5 years old, pure-tone average with the implant of between 25 and 30 dB HL (at 500, 1000, 2000 Hz) and voice detection between 20 and 25 dB HL (measured by visual reinforcement audiometry) at day of testing. Parents of the infants with CIs completed a questionnaire with detailed medical and developmental information to exclude additional medical problems other than hearing loss. Parents were interviewed by a certified communication disorders clinician regarding their child's auditory behavior and early speech production skills using the infant toddler meaningful auditory integration scale and the production infant scale evaluation (Robbins et al. 2004; Kishon-Rabin et al. 2009, respectively). The data of the questionnaires are summarized in Table 1. All electrodes were active on the day of testing.

The infants with NH met the following inclusion criteria: (1) full term at birth with an APGAR score of 9 to 10, (2) normal development and hearing as reported by well-care baby clinics, (3) no known neurological, anatomical, and/or physiological abnormalities according to parental reporting via a detailed questionnaire, (4) infant toddler meaningful auditory integration scale and production infant scale evaluation scores within 2 standard error (SE) of normative data (Kishon-Rabin et al. 2005), (5) hearing parents with no known familial history of hearing loss, and (6) parental reporting of no more than two ear infections during the past 6 months and no upper respiratory infections (including ear infection) on the day of testing.

All participating infants came from monolingual Hebrew-speaking homes.

Stimuli

Stimuli included a single CVCV bisyllabic nonsense pattern stressed on either the first or the second syllable (*/dóti/* and (*/dotí/*). Sixteen tokens of each stress pattern were recorded by a female Hebrew-native speaker. Stimuli were digitally recorded in a sound proof room via a JVC MV 40 microphone using the Sound-Forge software (version 4.5a) at a sampling rate of 48,000Hz and 16 bits quantization level.

Amplitudes were normalized without changing the intensity ratios between syllables within a word. Overall, intensity differences between tokens were not greater than ½ dB rms. Acoustical analyses of the duration, F0 and amplitude of all the tokens as well as of each of the vowels of the stressed and unstressed syllables within each token were conducted using the speech analyzing software PRATT (Boersma & Weenink 2013). The mean duration of *strong–weak* and the *weak–strong* tokens did not differ significantly ($p > 0.05$; M = 467.37 msec, SD = 9.3 and M = 469 msec, SD = 7.55, respectively). Similarly, the mean amplitude of *strong–weak* and the *weak–strong* tokens did not differ significantly ($p > 0.05$; M = 77.96 dB rms, SD = 0.19 and M = 77.95 dB rms, SD = 0.18, respectively). The mean F0, however, showed higher values (by 28 Hz) for the average weak–strong tokens (M = 218. 98 Hz, SD = 2.40) compared with the strong–weak ones (M = 190.35 Hz, SD = 2.36) [$t(30) = 29.37$, $p = 0.01$, $d = 12.03$].

Average within token measurements of duration, F0 and amplitude for each of the vowels in the stressed and unstressed syllables in the strong–weak */dóti/* and weak–strong tokens */dotí/* are summarized in supplemental Appendix A (http://links.lww.com/EANDH/A220). A significant difference was found for each of these measurements between the stressed and unstressed syllables within each type of stress patterns. The results of these analyses are also shown in supplemental Appendix A (http://links.lww.com/EANDH/A220). Comparison of these differences (between the stressed and unstressed syllables) between the two types of stress patterns revealed significantly larger duration difference in *strong–weak* tokens (mean difference = 81.65 msec, SD = 18.59) compared with *weak–strong* ones [mean difference = 66.25 msec, SD = 13.96; $t(30) = 2.634$, $p = 0.013$, $d = 1.32$]. Similarly, larger mean amplitude differences (between the stressed and unstressed syllables) were measured for *strong–weak* (mean difference = 11.28 dB, SD = 1.28) compared with *weak–strong* tokens (mean difference = 1.84 dB, SD = 2.34; Mann–Whitney $U = 0$, $p < 0.001$, $d = 5.01$). In contrast, larger differences in the mean F0 (between the stressed and unstressed syllables) were measured for the *weak–strong* tokens (mean difference = 47.97 Hz, SD = 5.19) compared with *strong–weak* ones (mean difference = 40.93 Hz, SD = 2.24). The difference was only 7 Hz but it was found to be statistically significant (Mann–Whitney $U = 21$, $p < 0.001$, $d = 1.13$).

From the 16 different tokens of each stress pattern, 4 files for each stress pattern were created for presentation during the experiment. Each speech file contained 16 tokens with silent interval of 600 msec between each token. The 4 files included different random orders of the 16 tokens. The mean duration of the final audio files for /d*otí*/ and /*dóti*/ trials was 17.75 seconds (range: 17.6 to 17.8) and 17.7 seconds (17.6 to 17.8), respectively.

Test Conditions

Three test conditions were used: a change from /dóti/ to /dotí/ (test condition A), a change from /dotí/ to /dóti/ (test condition B), and a control "no-change" condition from /dotí/ to /dotí/ or from /dóti/ to /dóti/ (test condition C). NH infants were randomly assigned to one of the three discrimination test conditions (A, B, or C). The infants with CI were randomly assigned to one of two discrimination test conditions (A and B). Only NH infants were assigned to the control condition because of the difficulty in recruiting CI infants. Summary of the age ranges of the participating infants as well as mean age and standard deviation, for each group of infants assigned to the different test conditions is shown in Table 2.

Procedure

Infants were tested using the visual habituation procedure (e.g., Best & McRoberts 2003; Houston et al. 2003). The infant

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TABLE 1. Background auditory information pre and postimplantation

No/Gender	Etiology	Unaided PTA (dBHL)	Unaided VD (dBHL) L, R	ABR (dBHL) L, R	Implanted Ear	Age at First Tuning (Month;day)	Age at Testing (Month;Day)	CI Use (in Month)	ITMAIS (Pre/Postimplant)	PRISE (Pre/Postimplant)`	CI Device and Strategy
1 F	Connexin	95	65, 55	85, 75	L	13;10	15;19	2	UA/22.5	18/40.9	NUC FREEDOM ACE
2 M	Connexin	100	95, NR	NR	L	11;26	13;28	2	0/55	18/40.9	NUC FREEDOM ACE
3 F	Connexin	NR	NR	NR	R	16;7	17;10	1	30/30	13/13	MEDEL CIS
4 F	Waarden-burg	NR	NR	NR	R	16;16	22;15	6	UA/100	UA/100	NUC FREEDOM ACE
5 F	Genetic (not Connexin)	110	90, 95	NR	R + L	12;10	13;16	1	7.5/7.5	7.5/15.9	NUC FREEDOM ACE
6 M	Connexin	NR	95, 105	85, NR	R	28;01	33;05	5	44/100	59/100	MEDEL C40+ CIS
7 F					R + L	22;07	28;12	6	UA/67.5	UA/100	COCHLEAR C5 ACE
8 F	Connexin	NR	NR	NR	R	13;10	17;20	4	UA/67.5	UA/90.9	NUC FREEDOM ACE
9 F	CMV	NR	NR	NR	R + L	10;20	12;25	2	UA/32.5	UA/29.5	MEDEL CIS
10 F	Connexin	NR	NR	NR	R + L	10;16	13;18	3	20/70	38/52	MEDEL OPUS 2 FSP
11 M	Unknown (not Connexin)	110	100, 100	NR	R	17;26	18	1	25/62.5	31.8/45.5	NUC FREEDOM ACE
12 M	Connexin	110	95, 100	NR	R	15;20	16;23	1	22.5/40	UA/50	NUC FREEDOM ACE
13 M	Unknown (not Connexin)	NR	NR	95, NR	L	20;20	21;28	1	2.5/12.5	34/43.18	NUC FREEDOM ACE
14 F	Connexin	110	105	110, NR	R	27;02	33;10	6	UA/100	9/100	NUC FREEDOM ACE
15 F	Meningitis	NR	NR	NR	R + L	18;27	21;01	2	UA/75	UA/59	NUC FREEDOM ACE
16 M	Connexin	NR	NR	NR	R + L	10;02	13;01	3	20/60	58/52	MEDEL OPUS 2 FSP
17 F	Meningitis	NR	NR	NR	R + L	18;26	21;01	2	UA/100	UA/79.5	COCHLEAR C5 ACE
18 M	Genetic (not Connexin)	NR	NR	NR	R + L	10;24	12;28	2	UA/52.5	UA/31.8	MEDEL C40+ CIS
19 F	Meningitis	NR	NR	NR	R	11;01	13;02	2	UA/77.5	UA/50	MEDEL C40+ CIS
20 F	CMV	NR	NR	NR	R + L	11;00	12;02	1	UA/7.5	UA/35	MEDEL C40+ CIS

Etiology, unaided pure-tone average (PTA in dB HL), unaided voice detection thresholds (in dB HL), responses to bone conduction auditory brainstem evoked response elicited by click, implanted ear, age at day of testing, CI use in months, auditory behavior (ITMAIS) and speech production (PRISE) questionnaires pre and postimplantation, and CI device. Note that first tuning was conducted between 3 and 4 weeks postimplantation. CI use was calculated from first tuning. At day of testing, proper functioning of the CI was confirmed.

ABR, auditory brainstem response; F, female; HI, hearing impaired; ITMAIS, infant toddler meaningful auditory integration scale; L, left; M, male; No, infant number; NR, no response at maximum output of audiometer @110 dB HL; PRISE, production infant scale evaluation; R, right; UA, unavailable; VD, voice detection.

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TABLE 2. Summary of age of participants: range, mean and standard deviation, for each group and test condition

Group (n)	Test Condition	Age Range	Mean Age (Month;Day)	SD (Month;Day)
CI (10)	A (dotí/ to /dóti/)	13;16–33;05	18;17	7;07
CI (10)	B (/dóti/ to /dotí/)	12;02–33;10	18;10	6;25
NH (16)	A (dotí/ to /dóti/)	11;00–14;28	13;01	1;21
NH (16)	B (/dóti/ to /dotí/)	11;06–14;27	12;17	1;15
NH (8)	C no change (/dotí/ to /dotí/)	11;13–14;04	12;13	1;25
NH (8)	C no change (/dóti/ to /dóti/)	11;15–14;02	12;15	1;22

**No significant difference was found between the ages in the 4 groups of normal-hearing infants and the 2 groups of CI infants.*
CI, cochlear implant; NH, normal hearing.

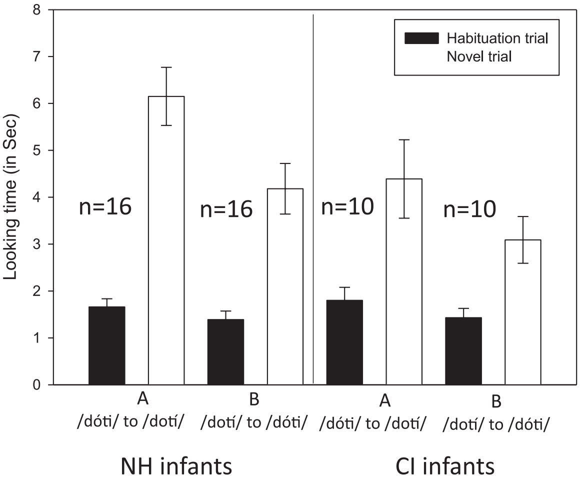

Fig. 1. Mean looking time and standard errors for the last habituation trial and the novel (dishabituation) trial in each test condition (A, B, and C) and for each group of infants: NH and with CI. CI, cochlear implants; NH, normal hearing.

was seated on the caregivers' lap in front of the monitor. The experimenter was seated outside the booth in the control room. Both the caregiver and experimenter listened to masking music (that was recorded with speech background) over headphones and were therefore blind to the stimulus on each trial. Stimuli were presented to the infants via loudspeakers at a comfortable level of 65 dB SPL.

All trials began by drawing infants' attention to the TV monitor using an attention getter (e.g., a small dynamic video display of a laughing baby's face). Then, habituation trials were initiated. During the habituation phase, the infant was presented with a visual display (blue and red static checkerboard) and up to 16 repetitions of the word (e.g., */dotí/*). Each habituation trial continued until the infant looked away from the checkerboard pattern for 1 second or until the maximum duration of the trial (18 seconds). These trials continued until the infant's average looking time to the visual display across 3 consecutive trials was 50% or less than the average looking time across the first 3 trials or until a maximum of 30 habituation trials was reached. When the habituation criterion was met, the infant was presented with 2 novel (dishabituation) trials, each consisting of up to 16 repetitions of a novel word (e.g., (*/dóti/*) presented with the same visual display as in the habituation phase. We expected infants to exhibit longer looking times during the novel trial than during the last habituation trial if they noticed the differences between the stress patterns (Horowitz 1974; Best et al.1988; Polka & Werker 1994).*

Parents signed a consent form before their infants were tested. The research was approved by the research Ethics Committee of Tel Aviv University and the Ethics Committee of the Chaim Sheba Medical Center.

Statistical Analysis

To ensure that the procedure did not produce a regression to the mean effect (i.e., longer looking times after meeting the habituation criteria regardless of what is presented), we analyzed the data from the control condition first. The mean looking times for the habituation and dishabituation trials in the no-change conditions were similar (for /dotí/ to /dóti/ M = 1.57, 1.67, SD = 0.50, 0.69, respectively, and for /dóti/ to /dóti/ M = 1.88, 1.96, SD = 0.75, 0.85, respectively). Paired *t* tests confirmed that the difference between the habituation and dishabituation trials were nonsignificant in both conditions ($p > 0.05$). Thus concluding that there is no "novelty effect" in the no-change condition.

After confirming the procedure, we continued the analysis of the two-test conditions. Repeated measures two-way analysis of variance was conducted with Stimuli (habituation, novel trial) as the within-subject variable and Group and Condition as the between-subject variables. For comparing data between two samples, *t* tests were used. When the samples were not normally distributed or they were not equal in variance, the Mann–Whitney *U* nonparametric statistic was used. Effect sizes were calculated using Cohen's *d* for *t* tests and eta squared (η^2) for analysis of variance. Note Cohen's (1988) convention for a large effect ($d = 0.8$; $\eta^2 = 0.26$), medium effect ($d = 0.5$; $\eta^2 = 0.13$) and small effect ($d = 0.2$; $\eta^2 = 0.02$).

RESULTS

The mean results for the last habituation and the first dishabituation trials in each Condition and Group are shown in Figure 1. Individual results are shown in supplemental Appendix B (http://links.lww.com/EANDH/A221).

As can be seen from Figure 1, mean looking times were longer for the novel trials compared with the last habituation trials across the two test conditions and the two groups of participants. The statistical analysis revealed a main effect for Stimuli [$F(1, 48) = 98.68$, $p = 0.0001$, $\eta^2 = 0.68$] suggesting that mean looking time for the novel trial (M = 4.62 sec) was longer compared with the habituation trial (M = 1.56 sec). A main effect was also found for condition [$F(1, 48) = 6.36$, $p = 0.02$, $\eta^2 = 0.11$] suggesting that looking time for test condition A (dotí/ to /dóti/) was longer compared with looking time for test condition B (dóti/ to /dotí/). The significant interaction Stimuli × Group [$F(1, 48) = 6.86$, $p = 0.01$, $\eta^2 = 0.125$] reflects longer looking times to the novel trials for the NH infants compared with those with CI as shown in Figure 2. Stimuli × Condition

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*There are several possible methods for dealing with spontaneous regression to the mean after the habituation criterion is met (Bertenthal et al. 1983). To minimize the possibility of a type I error, we took a conservative approach of using a design that included a control group and between-subjects analyses to test for discrimination. This is the same approach as used in the first implementation of a visual habituation procedure to assess speech perception (Horowitz 1974).

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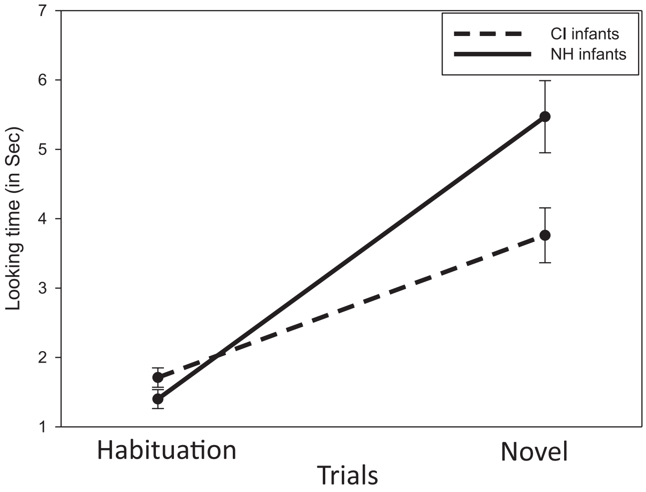

Fig. 2. Interaction between the mean looking time for the last habituation trial and the novel (dishabituation) trial and group of infants (NH and with CI). CI, cochlear implants; NH, normal hearing.

interaction [$F(1, 48) = 5.14$, $p = 0.03$, $\eta^2 = 0.09$] reflects that looking times (across the 2 groups of infants) during the novel trials were longer in test condition A (/dóti/ to /dotí/) compared with B (dóti/ to /dotí/) as shown in Figure 3. No main effect of group or significant Group × Condition or Stimuli × Group × Condition interactions were found ($p > 0.05$). A series of paired *t* tests following Bonferroni correction was conducted with adjusted alpha level set to 0.0125 per test (0.05/4). The results confirmed a significant difference between the means of the last habituation trial and the first novel trial in NH infants in test condition A [$t(15) = 8.12$, $p < 0.0001$, $d = 2.03$], and B [$t(15) = 5.5$, $p < 0.0001$, $d = 1.37$] and in CI infants in both test condition A [$t(9) = 3.47$, $p = 0.00$, $d = 1.09$], and B [$t(9) = 4.25$, $p = 0.002$, $d = 1.34$]. These results support the notion that both groups were able to discriminate between stress patterns regardless of the order of presentation. No correlation was found between duration of CI use and the novelty effect (the difference between looking time to the first novel trial and the last habituation trial).

DISCUSSION

The results of the present study support the following outcomes: (1) young hearing-impaired infants with CIs were able to discriminate between lexical stress patterns similarly to NH peers even after limited auditory experience with the CI device (1 to 6 months of device use), (2) infants with CI had a smaller novelty response (i.e., reduced discrimination) compared with NH infants, and (3) the order of presentation of the stimuli influenced discrimination: both NH and CI infants showed increased discrimination response when the stress pattern changed from the uncommon (*strong–weak* /dóti/) to the common (*weak–strong* /dotí/) lexical stress pattern in Hebrew compared with the reversed order.

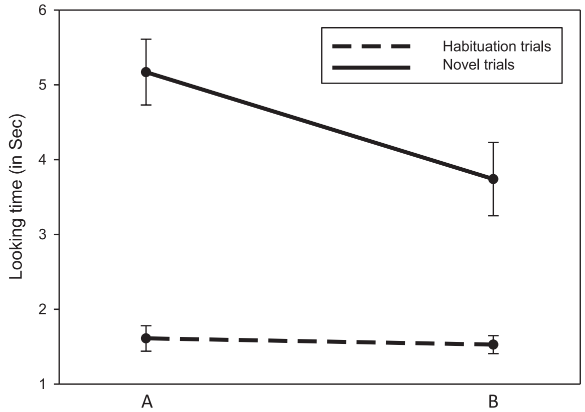

Fig. 3. Interaction between the mean looking time for the last habituation trial and the novel (dishabituation) trial and test conditions (A and B).

Our first finding that CI infants were able to discriminate between stress patterns after limited use of the CI device suggests that the acoustic information that mediates lexical stress is being transmitted successfully by the CI device. Studies show that the acoustic correlates of lexical stress in Hebrew include changes in F0, duration, and amplitude (Enoch & Kaplan 1969; Becker 2003). This is further confirmed in the present study where significant differences between the stressed and unstressed syllables within each type of stress pattern were found. Specifically, longer durations (80 and 40 msec), higher F0 (40.9 and 48 Hz), and increased amplitude (11.28 and 1.8 dB) were measured for the stressed compared with the unstressed syllables in the *strong–weak* and *weak–strong* lexical stress patterns, respectively. It is assumed that at least some of the CI infants were able to perceive some, if not all, of these differences. Not much has been reported on duration discrimination in CI users. In fact, the scarce available data are on gap duration discrimination (Sagi et al. 2009), which showed that overall, CI users performed considerably worse than NH, with some CI users unable to discriminate between 2 silent gaps that differed by 75 msec. The authors of the study concluded, however, that the poor results may be related to the age of the CI users as well as the relatively old speech processing strategies they used. In contrast, NH adults were reported having Weber fractions for duration discrimination, which varied between 6 and 30% depending on the standard duration, previous musical experience and task (e.g., Dooley & Moore 1988; Güçlü et al. 2011). In terms of the ability to utilize F0 cues, the differences in the average F0 between the stressed and unstressed syllables in the *strong–weak* and *weak–strong* stress patterns correspond to 20.5 and 24% of the speaker's F0 (198.25 Hz), respectively. These values are above the 4 to 13% DL for frequency reported for CI users (Geurts & Wouters 2001) suggesting that our CI infants were probably able to utilize F0 cues for discriminating between stressed and unstressed syllables. Similarly, the differences in amplitude are above the thresholds reported for CI users. Rogers et al. (2006) reported DL for intensity of 1.2 and 3.1 dB for NH and CI users, respectively. However, in their second experiment, they showed that when concurrent cues exist (as in our study), thresholds were reduced by half (i.e., to 0.6 and 1.55 dB, respectively) supporting the notion that our infants with CI had access to intensity cues as well. While it appears that infants with CI in the present study were sensitive to some or all cues for lexical stress, there is still the possibility that they were sensitive to a general acoustic cue that appeared in one lexical stress pattern but not in the other. Our measurements showed that the two types of stress pattern, *strong–weak* and *weak–strong* did not differ by their overall duration or intensity. However, the general average F0 of the /*weak–strong*/ tokens was found to be 28 Hz higher than that of the /*strong–weak*/ corresponding to approximately 14% of the F0 and just above

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the DL for frequency (Geurts & Wouters 2001). Thus, the possibility that they used this cue to differentiate between the lexical stress patterns although quite low, cannot be ruled out and warrants further investigation.

The findings of the present study suggest better access to suprasegmental features than those reported in the literature (e.g., Barry et al. 2002; Ciocca et al. 2002; Lee et al. 2002; Chatterjee & Peng 2008; Luo et al. 2012). As mentioned above, it is possible that in Hebrew, lexical stress is mediated by several concurrent acoustic cues, thus allowing more acoustic redundancy and therefore better accessibility compared with languages such as Cantonese where lexical tones are primarily mediated by changes in F0 (e.g., Barry et al. 2002; Ciocca et al. 2002; Lee et al. 2002). Another possible explanation for our better results than those previously reported may be related to the fact that the majority of our infants had CI devices with advanced speech processing strategies and stimulation rates that were high enough to accurately represent the modulating envelope. These CI devices allow for stimulation rates that are at least 4 to 5 times the frequency of the modulation (i.e., above 1000 Hz), which is sufficient to cover much of the pitch range (Green et al. 2004). In contrast, most studies that reported difficulty in perceiving Cantonese lexical tones included children who had CI devices with limited stimulation rates of approximately 300 pulses per second (e.g., Barry et al. 2002; Ciocca et al. 2002; Lee et al. 2002) which was too low to accurately represent the F0 or the frequency of the modulating envelope. Another important difference between the present study compared to others relates to the fact that our infants were implanted with the CI device under the age of 18 months. Other studies investigated pitch perception abilities in either postlingual hearing-impaired adults (e.g., Chatterjee & Peng 2008; Luo et al. 2012) or hearing-impaired children that were implanted at an older age (e.g., Barry et al. 2002; Ciocca et al. 2002; Lee et al. 2002). It is possible that the infants in the present study, who had a relatively short period of auditory deprivation and in the critical period for brain organization learned to utilize whatever cues that were available to them for perceiving lexical stress. In contrast, postlingually deafened adults with CI have acquired pitch information with acoustic hearing before their hearing impairment are limited in their ability to adapt to different cues once implanted with a CI (e.g., Kishon-Rabin et al. 2002). Future studies need to assess the relative weighting of each of the acoustic cues utilized for stress perception in CI users and how it differs between early implanted prelingual hearing impaired children compared with postlingual deafened adults.

The present findings are encouraging because they suggest that infants with CI possess basic auditory capabilities for discrimination of lexical stress patterns. The ability to discriminate between lexical stress patterns is known to be important for the early stages of language acquisition especially in languages with variable stress (such as Hebrew and English) in which stress signs various distinctions between words including semantic (e.g., /bíra/ “beer” versus /birà/ “capital city”), lexical (e.g., /nàal/ “shoe,” noun versus /naàl/ “locked,” verb) and morphological differences (e.g., /xatúl/ “cat,” singular, masculine gender, versus /xatulà/ “cat” singular, feminine gender; Bat-El 1993; Graf & Ussishkin 2003). Thus, the ability of CI infants to discriminate between stress patterns suggests that they are equipped with a basic and important skill for language acquisition. Caution should be taken, however, in extending these results to infants from other languages because languages vary in their type of stress pattern as well as in the acoustic cues that mark them (Peperkamp et al. 2010). Thus, further cross-linguistic studies are needed in order to assess the influence of the stress pattern of the language and its mediating cues on early speech perception performance of infants with CI.

The second finding of this study was that infants with CI showed average shorter looking times to the novel trial (i.e., reduced discrimination) compared with NH infants. One possible explanation for this outcome is that the cues for stress transmitted via the CI device were not readily available or robust enough for the infants with CI compared with NH. As mentioned earlier, NH listeners have more acoustic redundancy because the measured differences in duration, F0, and amplitude between the lexical stress patterns are considerably above their psychoacoustic thresholds (Moore 2003). In contrast, for infants with CI, these differences are closer to their psychoelectric thresholds and are therefore less available to them or require more listening effort or allocation of resources thus taxing on their discrimination process. Another possibility for the CI’s shorter looking time may be related to the limited experience the infants had with their CI (1 to 6 months), which was not comparable with the hearing experience of the control group of NH. It may be, that, with more hearing experience the CI infants may develop discrimination abilities similar to those of NH peers. Also, although no correlation was found between the duration of CI use and the novelty effect, it may be that the small range of CI use in this study limited the possibility of such an association. It is therefore possible that with more hearing experience, an association between experience with the CI and novelty effect will emerge. Finally, one cannot exclude the possibility that the auditory deprivation in the preimplant stage limited the development of higher-level attentional and cognitive aspects of auditory processing (e.g., Ponton & Eggermont 2001). Previous studies showed less attentional resources to auditory stimuli in CI infants compared with NH in the first year postimplantation even though they could discriminate between the different test stimuli (Houston et al. 2003; Kishon-Rabin et al. 2010; Segal & Kishon-Rabin 2011). These data together with that of the present study continue to support the notion that CI infants may be less tuned to listen and detect changes in the auditory signal even if the CI device can transmit sufficient auditory information to the central auditory system. Future studies are needed to determine the age and amount of hearing experience that are required for CI infants to reach comparable levels of performance to that of NH peers.

The third outcome of the study was that both NH infants and CI infants showed increased discrimination response when the change was from the uncommon *strong–weak* stress pattern (e.g., /dóti/) to the more common *weak–strong* stress pattern (/dotí/) stress pattern in the Hebrew language. If discrimination was based solely on detecting acoustic differences, then we would expect one of two possible outcomes: either discrimination would be independent of the order of presentation of the stimuli (i.e., the novelty effect from /dóti/ to /dotí/ should be the same as from /dotí/ to /dóti/), or, we would expect bias toward the type of lexical pattern that has more prominent differences in the acoustic cues between the stressed and unstressed syllables. The comparisons between stressed and unstressed syllables within tokens and between lexical stress patterns revealed

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that duration and amplitude cues were more prominent in the *strong–weak* lexical stress pattern, whereas the difference in F0 between the stressed and unstressed syllable was greater in the *weak–strong* stress pattern. This latter difference, which amounted to only 7 Hz (3.5% of the F0), while statistically significant, is less than the threshold for DL reported for CI (Geurts & Wouters 2001). Therefore, it is reasonable to assume that if discrimination was based only on acoustic cues, infants would have favored the longer and louder lexical pattern (i.e., the *strong–weak*) showing a greater novelty effect from the *weak–strong* to the *strong–weak* than vice versa. The finding that our infants showed asymmetry in favor of the *weak–strong* stress pattern supports language-specific explanation due to the fact that in Hebrew, the weak–strong stress pattern is more frequent than the strong–weak one in bisyllabic words (Segal et al. 2009). Therefore, it is possible that the common stress pattern of the Hebrew language (weak–strong) may have attracted infants' attention so that they were more sensitive to a change *to* it (dóti/ to /dotí/) than away *from* it (/dotí/ to /dóti/). These findings complement recent studies that have found asymmetries in stress pattern discrimination in German-learning infants—that is, stronger discrimination when a change is *to* the common stress pattern (strong–weak) than when a change is *from* it (Weber et al. 2004, 2005). There is also evidence to suggest that 4- to 5-month-old German and French learning infants show a positive mismatch response for the non-native stress patterns presented among common stress patterns stimuli of the target language (Friederici et al. 2007). The *positive* mismatch response was interpreted by the authors as a special effort in discriminating the uncommon stress pattern (*weak–strong* for German and *strong–weak* for French) due to the involvement of weaker or less activated memory structures (Friederici et al. 2007). Other evidence for the influence of "top–down" processing on stress pattern discrimination showed that 9-month-old Spanish infants successfully distinguished between stress-initial and stress-final pseudowords, while French infants of the same age, whose native language does not include variable stress, did not show discrimination ability (Skoruppa et al. 2009). Thus, we believe that our data show the influence of the statistical distribution of stress patterns in the language on its discrimination in both groups of infants suggesting that the CI device provides sufficient auditory details and listening experience for facilitating learning processes from the phonetic input of the native language. Nonetheless, one cannot rule out entirely the possibility that the small change in F0 within the *weak–strong* pattern or the overall higher F0 frequency of this pattern attracted infants' attention resulting in better discrimination. This requires further investigation.

The findings that CI infants with 1 to 6 months of device use showed evidence of listening bias to the common stress pattern of Hebrew was somewhat surprising considering existing data suggested that NH infants require at least 6 months of listening experience to develop a stress-pattern bias for their native language (Jusczyk et al. 1993; Höhle et al. 2009). A possible explanation for these findings may be related to the older age of the infants with CI in the present study compared with NH and therefore more cognitively mature. Similar findings were reported by Robbins et al. (2004) who attributed the rapid development of auditory skills in infants and toddlers following CI to the fact that they were older than their normally-hearing peers and therefore more cognitively advanced. In a different study, Thiessen and Saffran (2007) showed that 7- and 9-month-old NH infants were able to utilize a new pattern of lexical stress for segmentation after only 2 min of familiarization with the novel stimuli. Thus, it is possible that a few weeks of exposure to spoken Hebrew via the implant device were sufficient for 11 to 20 months old infants with CI to develop a listening bias to the common stress pattern of the language. It is also possible that the good performance shown after such a limited time with the implant may be related to the task that was used. It has been suggested that discrimination tasks are easier, especially for children compared with tasks where the child is required to recognize the direction of the pitch or name it (e.g., Barry et al. 2002). Thus, factors related to cognition and linguistic knowledge may have confounded results of earlier studies that involved pitch perception tasks in children.

Overall, the results of the present study provide first evidence that infants with bilateral profound sensorineural hearing loss who use CIs develop prosodic discrimination skills soon after receiving their CI device. The ability to do so provides them with an important skill to support further language acquisition (Jusczyk et al. 1999). The present pattern of results is in support of a discrimination model in which both auditory capabilities and "top–down" interactions are involved. That is, the CI infants could detect changes between stressed and unstressed syllables after which they developed a bias for the more common *weak–strong* stress pattern in Hebrew. The latter suggests that infants with CI were able to extract the statistical distribution of stress patterns by listening to the ambient language even after limited use with the CI device. Thus, in relation to the processing of lexical stress patterns, infants with CI followed similar developmental milestones as hearing infants, establishing important prerequisites for early language acquisition.

Finally, the present findings support the notion that the CI device transmits effectively prosodic cues thus allowing infants with CI to perceive changes in patterns of Hebrew lexical stress. The relative contribution of amplitude, F0 and duration cues to the perception of lexical stress in young HI infants with CI is of interest and importance especially in languages with variable lexical stress patterns and should be investigated in future studies.

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