Production of contrast between sibilant fricatives by children with cochlear implants[a)]

Ann E. Todd,[b)] Jan R. Edwards,[b),c)] and Ruth Y. Litovsky[b)]
University of Wisconsin Waisman Center, 1500 Highland Avenue, Madison, Wisconsin 53705

(Received 3 August 2010; revised 13 September 2011; accepted 16 September 2011)

Speech production by children with cochlear implants (CIs) is generally less intelligible and less accurate on a phonemic level than that of normally hearing children. Research has reported that children with CIs produce less acoustic contrast between phonemes than normally hearing children, but these studies have included correct and incorrect productions. The present study compared the extent of contrast between correct productions of /s/ and /ʃ/ by children with CIs and two comparison groups: (1) normally hearing children of the same chronological age as the children with CIs and (2) normally hearing children with the same duration of auditory experience. Spectral peaks and means were calculated from the frication noise of productions of /s/ and /ʃ/. Results showed that the children with CIs produced less contrast between /s/ and /ʃ/ than normally hearing children of the same chronological age and normally hearing children with the same duration of auditory experience due to production of /s/ with spectral peaks and means at lower frequencies. The results indicate that there may be differences between the speech sounds produced by children with CIs and their normally hearing peers even for sounds that adults judge as correct.
[DOI: 10.1121/1.3652852]

PACS number(s): 43.70.Dn, 43.70.Mn [CHS] Pages: 3969–3979

I. INTRODUCTION

Most studies that have analyzed the speech of children with cochlear implants (CIs) have examined how intelligible these children are (e.g., Chin *et al.*, 2003; Peng *et al.*, 2004) or how accurately they produce phonemes (e.g., Blamey *et al.*, 2001; Tobey *et al.*, 2007; Tomblin *et al.*, 2008). While these studies have generally observed that children with CIs have poorer speech production than is expected from their peers with normal hearing (NH), their conclusions are limited by the fact that accuracy and intelligibility are based solely on adult listeners' judgments. There is little research on whether the speech of children with CIs differs from the speech of children with NH on a subphonemic level. The present study examined the production of the fricatives /s/ and /ʃ/ by children with CIs on a subphonemic level. The primary goal was to determine whether productions of /s/ and /ʃ/ by children with CIs have less acoustic contrast than those of children with NH.

There are at least two reasons why children with CIs might produce less contrast between /s/ and /ʃ/ than children with NH. First, in children with NH, there is a protracted period of acquisition of the contrast between /s/ and /ʃ/ (Nittrouer *et al.*, 1989; Nittrouer, 1995; Nissen and Fox, 2005; Li *et al.*, 2009). This finding suggests that speaking and listening experience play a role in the development of this contrast. Children with CIs have less speaking and listening experience than children with NH of the same age because they go through a period of auditory deprivation before receiving a CI. Furthermore, even once implanted, children with CIs have poorer speech perception than children with NH (e.g., Summerfield *et al.*, 2002; Eisenberg *et al.*, 2003; Grieco-Calub *et al.*, 2009). This deficiency in auditory perception could make speech acquisition a more prolonged process for children with CIs than for children with NH, which could result in a slower acquisition of contrasts such as /s/ and /ʃ/. The second reason is that children with CIs receive degraded auditory input that may be insufficient for them to hear the contrast between /s/ and /ʃ/ in other speakers' productions and in their own productions (Dorman *et al.*, 2000). In particular, differences between productions of /s/ which are highly contrastive with /ʃ/ and productions of /s/ that are less contrastive with /ʃ/ (and vice versa) may be imperceptible for children with CIs. Without this auditory information, children with CIs would be limited in their ability to learn to produce the contrast between /s/ and /ʃ/.

A. Perception of sibilant fricatives

Auditory discrimination of /s/ and /ʃ/ can be difficult for children with CIs. In a study by Summerfield *et al.* (2002), children with CIs were on average less than 60% correct in discriminating between the words *see*, *Sue*, *she*, and *shoe*. Discrimination errors were likely largely due to difficulty in discriminating between /s/ and /ʃ/ rather than /i/ and /u/, since consonant discrimination is more difficult than vowel discrimination for children with CIs (Kishon-Rabin *et al.*, 2002). These findings are not surprising because listeners with NH seem to rely on the difference in the spectral characteristics of the frication of /s/ and /ʃ/ (Hedrick and Ohde, 1993) to identify these sounds, and individuals with CIs hear with poor spectral resolution (e.g., Friesen *et al.*, 2001).

[a)]Portions of this work were presented at the Conference on Implantable Auditory Prostheses, Tahoe, CA 2009; Symposium on Research in Child Language Disorders, Madison, WI, 2009; and the 159th meeting of the Acoustical Society of America, Baltimore, MD, 2010.
[b)]Also at Department of Communicative Disorders, Goodnight Hall, 1975 Willow Drive, Madison, Wisconsin 53706.
[c)]Author to whom correspondence should be addressed. Electronic mail: jedwards2@wisc.edu

Furthermore, the performance of young children tends to suffer more than that of adults when spectral resolution is limited (Eisenberg *et al.*, 2000). Besides limitations in spectral resolution, /s/ and /ʃ/ can have spectral energy that is above the upper frequency limit of a typical CI (i.e., approximately 8000 Hz) which may also impede the ability of individuals with CIs to accurately identify these sounds.

While it has been found that children with CIs can have difficulty discriminating between /s/ and /ʃ/, it is not the case that these two phonemes are indistinguishable to individuals who use CIs. Summerfield *et al.* (2002) found a wide range of performance by children and adults with CIs in discriminating between /s/ and /ʃ/, and also found that children who had used their implants longer had better discrimination performance. Furthermore, studies on phoneme identification by high-performing adults with CIs have shown that perceptual confusions between /s/ and /ʃ/ are relatively uncommon (Dorman *et al.*, 1990; Munson *et al.*, 2003). These findings suggest that at least for some individuals, CIs provide sufficient acoustic information for them to discriminate between /s/ and /ʃ/. This is consistent with the findings that differences are apparent in the electrode output of the Ineraid cochlear implant between the sounds /s/ and /ʃ/ as produced by an adult female speaker (Matthies *et al.*, 1994).

Although it has been found that some individuals with CIs can discriminate between /s/ and /ʃ/, subtle within-category discriminations are more challenging. Lane *et al.* (2007a) found that postlingually deafened adults with CIs were less able than adults with NH to discriminate between stimuli on an /s/ – /ʃ/ continuum. Even small differences in auditory discrimination have been found to be related to reduced production of contrast in individuals with NH. In a study by Perkell *et al.* (2004), adults who performed worse on an auditory discrimination task of stimuli that formed a continuum between /s/ and /ʃ/ also produced less contrast between /s/ and /ʃ/. Perkell and colleagues suggested that children with poorer auditory discrimination skills do not learn to produce speech sounds as contrastively since they are less aware of the difference between productions of a sound that are more or less contrastive with another sound. If this is the case, then children with CIs should be expected to produce less contrast between /s/ and /ʃ/ than children with NH, because of their poorer auditory discrimination abilities.

B. Spectral analysis measures

The sounds /s/ and /ʃ/ are both voiceless sibilant fricatives. They are produced with air flowing through a constriction between the tongue and the hard palate. The sound /s/ is produced with the constriction more forward in the vocal tract and with a shorter constriction than /ʃ/. The spectral shapes of /s/ and /ʃ/ are related to the size of the cavity in the vocal tract anterior to this constriction and to the size of the constriction (e.g., Summerfield *et al.* 2002). The spectra of /s/ and /ʃ/ are each characterized by spectral peaks, the spectral peaks of /s/ being typically higher in frequency than the spectral peaks of /ʃ/. The exact spectral shapes of /s/ and /ʃ/ vary across speakers and contexts (Boothroyd and Medwetsky, 1992; Stevens, 2000).

Various measures have been used to quantitatively differentiate the fricative spectra of /s/ and /ʃ/ (see Newman *et al.*, 2001). The spectral mean (i.e., first spectral moment) is one measure that has been used to differentiate these sounds (Forrest *et al.*, 1988; Nittrouer, 1995). It consists of the frequencies of the spectral components weighted by their normalized amplitudes. As such, the spectral mean reflects information from the entire spectrum. Thus from changes in the spectral mean, it is difficult to know which articulatory changes took place. A measure of the frequency of the highest spectral peak can also differentiate /s/ and /ʃ/ (Jongman *et al.*, 2000; Fox and Nissen, 2005). This measure tends to relate to articulation in that it can be an indicator of the size of the cavity in the vocal tract anterior to the constriction. However, in cases in which there are two or more prominent peaks with similar amplitudes, the location of the highest spectral peak is more difficult to interpret. In this study, both the spectral mean and the spectral peak were calculated for the productions of /s/ and /ʃ/.

C. The current study

The present study sought to expand on the findings of previous studies which have examined the productions of /s/ and /ʃ/ by children with CIs. Studies have shown that children who use CIs produce less acoustic contrast than children with NH when attempting to produce /s/ and /ʃ/ (Uchanski and Geers, 2003; Mildner and Liker, 2008; Liker *et al.*, 2007). In these studies, all productions of target /s/ and /ʃ/ were included in the acoustic analyses as long as the attempts were fricatives.[1] Children with CIs in general have low accuracy for the production of /s/ (Blamey *et al.*, 2001), and therefore, it is uncertain whether substitutions of other fricatives for /s/ (or for /ʃ/) influenced the results of the acoustic analyses. The present study therefore examined the contrast between /s/ and /ʃ/ only for productions that were transcribed as correct.

A second aim of this study was to compare the speech production of children with CIs to that of children with NH of the same hearing age and to that of children with NH of the same chronological age. A child's hearing age is the amount of time that child has been exposed to auditory stimulation, and in this study was defined for the children with CIs as the time since activation of the first CI (Flipsen and Colvard, 2006). If duration of auditory experience is controlled for in this way and differences in the production of contrast by children with CIs and children with NH are found, this would suggest that the production of contrast by children with CIs is influenced by the degraded auditory input they receive through their CIs. It was hypothesized that children with CIs would produce less acoustic contrast between /s/ and /ʃ/ than both comparison groups of children with NH given that they have less auditory experience than their chronological-age peers, and given their degraded auditory input relative to both comparison groups.

II. METHOD

A. Participants

Participants were children between the ages of 4 to 9 years who use CIs (n = 39) and children with NH who are typically developing and were between the ages of 2 to 7 years (n = 43). The children with CIs were participants in a larger study on binaural and spatial hearing, and were recruited from various cochlear implant centers around the United States. They all traveled to Madison, Wisconsin, where the testing took place. All of the children had CIs in both ears, and had been implanted with their first CI before 2.5 years of age, with the exception of one child who was implanted at the age of 5 years, 2 months. All of the parents described their child's main mode of communication as auditory/oral except one parent who reported that his/her child used total communication. Recordings from six children with CIs were not included due to one of the following: errors made in the recording procedure (n = 2), a possible diagnosis of pervasive developmental disorder (n = 1), or no correct productions of either /s/ or /ʃ/ (n = 3). Characteristics of the children with CIs who were included in the analyses (n = 33) are shown in Table I.

Data for two of the children with NH were obtained in Madison, Wisconsin under circumstances identical to those under which the children with CIs were tested. The remainder of that data set was from a database of audio recordings of children's speech (Edwards and Beckman, 2008). These recordings had been obtained using the same stimuli and procedures as those used for the children with CIs, for the purposes of a larger study. These children were recruited from schools and day care centers in Columbus, Ohio, where the recordings were made. All children with NH passed a hearing screening which consisted of either otoacoustic emissions within normal range at 2000, 3000, 4000, and 5000 Hz, or pure tone audiometry thresholds within normal limits from 250 to 8000 Hz at octave intervals. None of the children with NH scored lower than one standard deviation below the mean on norm-referenced tests of articulation (Goldman and Fristoe, 2000), receptive vocabulary (Brownell, 2000), expressive vocabulary (Williams, 1997), or non-verbal IQ (Burgemeister *et al.*, 1972). Non-verbal IQ scores were available only for children above 3.5 years of age and standardized test results were unavailable for three of the children with NH. The children with CIs and the children with NH were all English speakers.

Twenty-one of the 33 children with CIs were compared to children with NH matched to the children with CIs on chronological age (within four months) and sex. Thirty-two of the 33 children with CIs were compared to children with NH matched to the children with CIs on hearing age (within four months). The hearing age of each child with CIs was calculated by subtracting the age at which the child's first CI was activated from the child's chronological age. Not every child with CIs was included in each comparison due to the inability to match children with NH of a close enough chronological age or hearing age to the children with CIs. Table II shows the characteristics of each group.

B. Stimuli

Table III shows the words elicited from the children for this study. There were nine words with /s/ in the initial position and nine words with /ʃ/ in the initial position. Following /s/ and /ʃ/ was a vowel from one of three vowel categories (approximately /i/, /ɑ/, /u/) which were distributed evenly throughout the stimuli. Vowels producing similar coarticulatory effects were grouped together in the same category. That is, /ɑ/, /ɔ/, and /ʌ/ were in the same category; /i/ and /ɪ/ were in the same category; and /u/ and /ʊ/ were in the same category. At least 30 additional words that started with sounds other than /s/ and /ʃ/ were intermixed with these words and were elicited from the children. The children with NH repeated more words than the children with CIs including more words that started with /s/ and /ʃ/ for the purposes of the larger study in which they were participants. Productions elicited by these words were not included in the analysis comparing the productions of the children with CIs to those of the children with NH.

Auditory stimuli were created by recording an adult female saying the target words in a child-directed speech register. Recordings were made at a 22 500 Hz sampling rate. Due to the sampling rate, stimuli did not extend above 11 025 Hz. This upper limit is more than adequate to allow for correct identification of /s/ (and /ʃ/) (Stelmachowicz *et al.*, 2001). There is the possibility that not hearing frequencies above 11 025 Hz might cause the children with NH to produce /s/ at lower frequencies. However, this effect if present, is expected to be minor, and should only lessen differences between the children with CIs and the children with NH, since 11 025 Hz is above the range of frequencies presented to children with CIs.

Five tokens of each word were recorded. Stimulus quality was tested by having five adult native English speakers repeat after each auditory stimulus. The adults participated individually. Stimuli were presented to the adults over loudspeakers, and the productions of the adults were recorded and judged for accuracy by an adult native English speaker. The inclusion criterion for the stimuli was correct production by at least 4 out of 5 of the adults. Three tokens of each stimulus word were included in this study.

Visual stimuli consisted of color photographs that corresponded to the auditory stimuli. For example, for the auditory stimulus *sister*, there was a photograph of two similar-looking girls with their arms around each other. The order of the stimuli was randomized.

C. Procedure

The children with CIs and the children with NH who participated in Wisconsin were recorded in a sound-attenuated booth, while the children with NH who participated in Ohio were recorded in a quiet room at their school or daycare center. The target words were elicited by a picture-prompted auditory repetition task. Auditory stimuli were presented over Audix PH5-VS loudspeakers which present frequencies from 75 Hz to 20 kHz for the children recorded in Wisconsin and over lower-quality Radio Shack 40–146 loudspeakers which present frequencies up to 15 kHz for the children recorded in Ohio. Visual stimuli were presented on a laptop computer screen. The children were provided with ten practice trials consisting of words beginning with various sounds. A single production of each

TABLE I. Characteristics of the children with cochlear implants.

Participant	Sex	Age	Age at 1st Implant	Age at 2nd Implant	Age of ID[c]	Etiology	First Implant (Device, Strategy, Ear)	Second Implant (Device, Strategy, Ear)
CIAW[a]	M	7.68	1.21	5.47	0;3	CMV	N24, ACE, R	Freedom, ACE, L
CIAY[b]	M	9.22	5.16	6	3;1	unknown	N24, ACE, R	N24, ACE, L
CIBB[b]	F	6.98	0.6	0.65	0;1	Meningitis	N24, ACE, R	N24, ACE, L
CIBT[b]	M	6.76	2.25	4.61	1;3	unknown	N24, ACE, R	Freedom, ACE, L
CIBU[b]	M	6.22	1.13	5.07	birth	Connexin	C40+, CIS+, L	PULSARci 100, CIS+, R
CIBV[a,b]	M	5.06	1.42	1.95	birth	Connexin	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L
CIBW[a,b]	F	4.98	1.04	3.78	birth	Connexin	N24, ACE, R	Freedom, ACE, L
CICB[a,b]	F	4.25	0.86	2.07	birth	Connexin	N24, ACE, R	Freedom, ACE(RE), L
CICF[a,b]	F	4.49	1.4	2.36	1;1	Meningitis	Freedom, ACE, R	Freedom, ACE, L
CICK[a,b]	M	4.63	1.11	1.31	1;0	Connexin	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L
CICL[a,b]	M	4.85	1.42	2.81	1;0	Connexin	Freedom, ACE(RE), R	Freedom, ACE, L
CICM[a,b]	M	4.36	1.07	3.15	birth	Connexin	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L
CICN[a,b]	F	4.1	1.31	2.87	birth	genetic	Freedom, ACE(RE), R	Freedom, ACE, L
CICY[a,b]	M	5.7	1	4.65	0;3	unknown	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L
CIDF[a,b]	F	5.93	1.14	5.47	birth	unknown	N24, ACE, R	Freedom, ACE, L
CIDG[a,b]	F	4.29	1.09	3.83	birth	unknown	N24, ACE, R	Freedom, ACE, L
CIDJ[b]	F	7.11	1.62	5.04	1;0	unknown	N24, ACE, R	Freedom, ACE, L
CIDN[b]	M	7.08	1.16	6.13	birth	genetic	C40+, CIS+, L	PULSARci 100, CIS+, R
CIDO[a,b]	F	5.85	2.32	4.68	1;3	LVAS	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L
CIDP[a,b]	F	4.93	0.93	2.71	birth	Connexin	C40+, CIS+, L	PULSARci 100, CIS+, R
CIDQ[b]	F	6.6	0.82	4.34	birth	unknown	N24, ACE, R	Freedom, ACE, L
CIDR[a,b]	F	4.56	1.82	2.57	birth	unknown	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L
CIDT[a,b]	F	6.35	1.56	3.14	0;3-0;6	Usher Syndrome	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L
CIDV[b]	F	6.48	2.12	3.46	1;1	Connexin	Freedom, ACE, L	N24, ACE, R
CIDW[a,b]	M	5.37	2.21	4.97	1;6	unknown	HiRes 90 K/HiFocus, HiResP w/Fidelity 120, L	HiRes 90 K/HiFocus, HiResP w/Fidelity 120, R
CIDX[b]	M	6.86	1.42	2.6	birth	Connexin	N24, ACE, R	N24, ACE, L
CIDY[a,b]	M	5.97	1.12	2.73	0;1	unknown	C40+, CIS+, R	PULSARci100, HDCIS, L
CIDZ[b]	F	7.43	2.11	4.95	2;0	Connexin	N24, ACE, R	Freedom, ACE, L
CIED[b]	F	6.45	2.25	3.13	1;8	LVAS	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L
CIEF[a,b]	F	5.87	1.35	4.84	0;9	unknown	N24, ACE, R	Freedom, ACE, L
CIEG[b]	M	6.11	1.38	4.9	1;0	Connexin	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R	HiRes 90 K/HiFocus, HiRes-P, L
CIEH[a,b]	M	4.14	1.07	1.07	birth	unknown	Freedom, ACE, R	Freedom, ACE, L
CIEI[a,b]	M	5.92	1.09	2.72	birth	unknown	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, L	HiRes 90 K/HiFocus, HiRes-P w/Fidelity 120, R

[a]Child included in the chronological age comparison.
[b]Child included in the hearing age comparison.
[c]Years; months.

word was elicited unless the child said the wrong word or the child's production was difficult to hear in which case a subsequent token was immediately elicited using the same stimulus item. The children's productions were digitally recorded at a sampling rate of 44 100 Hz. The recordings were made via a tabletop microphone connected to a Marantz PMD660 digital recorder. The children with NH were recorded in one or two sessions that were at the most 12 days apart, while the children with CIs were recorded in a single session.

D. Transcription

Trained native speakers transcribed the initial sounds of the children's word productions using a combination of the auditory signal, spectrogram, and waveform. Each initial sound was transcribed unless a child's production could not be heard. The transcribers coded each production as correct or incorrect relative to the target sound. Distortions, substitutions, and deletions of the sounds /s/ and /ʃ/ were considered incorrect productions. The transcribers coded each of these

TABLE II. Characteristics of the groups made up of children with cochlear implants (CI) and normally hearing children (NH). Mean ages are shown with standard deviations in parentheses.

Group	N	M/F	Age	Hearing Age	Age at 1st implant	Age at 2nd implant
Chronological age comparison						
CI	21	10/11	5.20(0.91)	3.89(0.93)	1.31(0.39)	3.29(1.30)
NH	21	10/11	5.17(0.90)	5.17(0.90)	NA	NA
Hearing age comparison						
CI	32	15/17	5.77(1.18)	4.26(0.98)	1.51(0.81)	3.57(1.44)
NH	32	17/15	4.25(1.00)	4.25(1.00)	NA	NA

three error types in the case of incorrect productions, and wrote the substituted sound in the case of substitution errors. One transcriber transcribed the productions of 41 of the normally hearing children. Another transcriber transcribed the productions of all of the children with CIs and the production of two of the children with NH.

Inter-transcriber reliability was calculated separately for the children with CIs and the children with NH using an additional transcriber for the children with CIs and another for the children with NH. The calculation included the /s/ and /ʃ/ productions of 20% of the participants: 7 children with CIs (two 4-year-olds, two 5-year-olds, two 6-year-olds, and one 7-year-old), and 9 normal-hearing children (three 3-year-olds, three 4-year-olds, and three 5-year-olds). Phoneme-by-phoneme inter-rater reliability for accuracy (correct/incorrect) judgments was 93% for the children with CIs and 87% for the children with NH. In the cases of disagreements, the judgments of the first transcribers were used.

E. Spectral analysis

Children's productions of /s/ and /ʃ/ which came from their first attempts at producing the stimulus words and which were judged as correct were analyzed acoustically. For each production, the waveform and spectrogram were viewed. The onset of frication was marked where there was an increase in energy in both the waveform and the spectrogram. The end of frication was marked at the first glottal pulse of voicing. From these markings, the midpoint of the fricative was calculated. The spectrum was calculated from the middle 40 ms of the fricative using the multitaper method with seven data tapers (Percival and Walden, 1993; Blacklock, 2004). No pre-emphasis was used. Spectral means were calculated from each spectrum over the range of frequencies from 200 Hz to 11 025 Hz by taking the weighted mean of the frequencies in the spectrum with frequencies weighted by their normalized power. The frequency with the highest amplitude, the spectral peak, was found from each spectrum in the frequency range from 500 Hz to 11 025 kHz. Five hundred Hz was used as a lower cutoff frequency to avoid any identification of peaks below 500 Hz, whereas 200 Hz was used as a lower cutoff frequency for the spectral mean calculation to reduce non-speech noise.

TABLE III. Target words.

	/ɑ/, /ɔ/, /ʌ/	/i/, /ɪ/	/u/, /ʊ/
/s/	soccer	seashore	super
	sauce	sister	soup
	sun	seal	suitcase
/ʃ/	shark	sheep	chute
	shop	shield	shoe
	shovel	ship	sugar

F. Simulation of electrode output of /s/ and /ʃ/

In order to examine how a child with CIs might hear the sounds /s/ and /ʃ/ in his/her own speech, the productions of /s/ and /ʃ/ by one of the children with NH (female; 6 years, 0 months) were processed to simulate the processing of a CI. Two productions of /s/ and two productions of /ʃ/ which were judged as correct by two transcribers and which were different from each other in their spectral peak locations and spectral means were chosen for this analysis. These productions of /s/ and /ʃ/ came from the child's productions of the words *sister*, *safe*, *chute*, and *shield*. The middle 40 ms of each of the four fricative productions was extracted using a Hamming window. The average intensity level of each of the four signals was scaled to the same level. Pre-emphasis was applied to each signal using a high pass 1st order Butterworth filter with a cutoff frequency of 1200 Hz. Subsequently, each signal was band pass filtered using eight channels of 4th order Butterworth filters with corner frequencies logarithmically spaced between 200 Hz and 8 kHz. The envelope of each channel was extracted using a 2nd order Butterworth filter with a 400 Hz cutoff frequency, and was used to modulate the amplitude of noise bands with bandwidths equivalent to the bandwidth of each filter. Eight kHz was chosen as an upper cutoff frequency, because this was the upper cutoff frequency of the CIs for most of the children in this study. Eight channels of spectral information were chosen because it has been found that for adults with CIs speech perception performance in quiet does not increase much beyond eight channels (see Shannon, 2002).

III. RESULTS

A. Accuracy results

The effects of consonant (/s/ vs /ʃ/), group (CI vs NH), and the interaction between consonant and group on accuracy were tested using likelihood ratio tests on generalized linear mixed-effect models that included random intercepts for participants (e.g., see Jaeger, 2008). Group was a between-subject effect. Consonant was a within-subject effect. The test statistic of each likelihood ratio was analyzed using a parametric bootstrap analysis. That is, the test statistic of each likelihood ratio was compared to a distribution calculated by repeatedly simulating data from the model that did not include the independent variable of interest.

When the accuracy of the children with CIs was compared to that of their chronological-age peers, the effect of consonant was significant ($X^2[1] = 40.02$, $p<0.001$). Both groups produced /ʃ/ more accurately than /s/. The effect of group ($X^2[1] = 12.38$, $p = 0.1$) and the interaction between consonant and group ($X^2[1] = 2.30$, $p>0.12$) were not significant. While the mean percent of /s/ and /ʃ/ productions by the children with CIs that were transcribed as correct (mean = 55.8, SD = 22.2 for /s/ and mean = 75.0, SD = 26.2 for /ʃ/) was lower than that of the children with NH (mean = 72.8, SD = 25.4 for /s/ and mean = 92.2, SD = 12.2 for /ʃ/), this difference was not significant most likely due to the high amount of variability for both groups of children.

When the accuracy of the children with CIs was compared to that of their hearing-age peers, the effect of consonant was significant ($X^2[1] = 54.53$, $p<0.001$). Again, both groups produced /ʃ/ more accurately than /s/. The effect of group ($X^2[1] = 0.68$, $p>0.40$) and the consonant by group interaction ($X^2[1] = 0.52$, $p>0.46$) were not significant. The mean percent of correct productions by the children with CIs (mean = 62.0, SD = 24.5 for /s/ and mean = 82.5, SD = 23.7 for /ʃ/) was similar to that of the children with NH (mean = 67.8, SD = 23.5 for /s/ and mean = 83.4, SD = 19.9 for /ʃ/). It must be kept in mind that productions of children who did not produce any correct productions of /s/ or /ʃ/ during the elicitation task were not included in the present study.

Table IV shows the most frequent errors produced for /s/ and /ʃ/ by the children in the chronological age comparison. The errors that the children with CIs produced differed from the errors of the children with NH more when the target sound was /s/ than when the target sound was /ʃ/. When the children with CIs produced /s/ incorrectly, they most frequently substituted [f], [θ], or a stop. Surprisingly, stop substitutions for /s/ were produced even by two children with CIs who were as old as six years of age and had hearing ages of 4;8 and 6;4 (years;months). When the children with NH produced /s/ incorrectly, they most frequently produced [ʃ], [θ], or [ts]. Both groups of children produced [tʃ] and [s] as the most frequent substitutions when the target sound was /ʃ/. This same pattern was also true for the hearing age comparison. Therefore, the errors of the children in the hearing age comparison are not shown.

TABLE IV. The number of tokens produced per type of error for /s/ and /ʃ/ by the children with cochlear implants (CI) and the normally hearing children (NH) in the chronological age comparison group, and the number of children who produced those errors.

	CI Number of tokens	Number of children (n = 21)	NH Number of tokens	Number of children (n = 21)
Errors for /s/				
[f]	21	11	0	0
[θ]	13	8	16	6
[ʃ]	5	4	13	9
[ts]	8	5	9	6
Stops	16	9	1	1
distortions	10	4	3	2
Other	12	6	3	3
Total	85		45	
Errors for /ʃ/				
[s]	6	4	3	1
[tʃ]	23	13	7	5
distortions	6	2	0	0
Other	12	7	4	4
Total	47		14	

B. Spectral analysis results

The effects of consonant (/s/ vs /ʃ/), group (CI vs NH), and the interaction between consonant and group on the spectral measures (spectral peak and spectral mean) were tested using likelihood ratio tests on linear mixed-effects models (e.g., see Baayen *et al.*, 2008) which included random intercepts for participants. The effect of group was a between-subject effect, and the effect of consonant was a within-subject effect. Likelihood ratio tests were used as opposed to F-tests due to the unbalanced number of tokens for each participant. Again, the test statistic of each likelihood ratio was analyzed using a parametric bootstrap analysis. The interaction between group and consonant was of most interest, as a significant interaction would suggest that one group produced less contrast between /s/ and /ʃ/ than the other group (Nittrouer, 1995). Since the results of the analysis of spectral peaks and spectral means were similar, only the results of statistical tests for the spectral peaks are reported unless a difference in significance was found between the two analyses. Effects were considered significant when $p < 0.05$.

Average spectral means for the /s/ and /ʃ/ productions of the children in the chronological age comparison were 6656 Hz and 5328 Hz, respectively, for the children with CIs, and 7699 Hz and 5223 Hz for the children with NH. For the children in the hearing age comparison, average spectral means for the /s/ and /ʃ/ productions were 6577 Hz and 5123 Hz, respectively, for the children with CIs, and 7338 Hz and 5460 Hz for the children with NH.

Figures 1 and 2 show the spectral peaks of productions of /s/ and /ʃ/ by the children in the chronological age comparison and the children in the hearing age comparison, respectively. In both figures, spectral peaks of /s/ were higher than spectral peaks of /ʃ/. This was confirmed by the statistical analysis. The effect of consonant was significant for both of the mixed-effects models: the model for the chronological age comparison ($X^2[1] = 298.04$, $p<0.001$) and the model for the hearing age comparison ($X^2[1] = 371.86$, $p<0.001$).

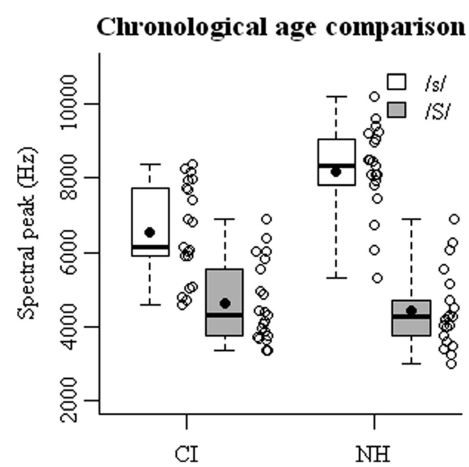

FIG. 1. Boxplots representing the range of the participants' mean spectral peaks of productions of /s/ and /ʃ/ by the children with cochlear implants (CI; n = 21) and the normally hearing children (NH; n = 21) in the chronological age comparison group. Horizontal bars represent the median. Whiskers extend to the farthest data points. Data points are shown to the right of the box plots. Group means are shown by the black points.

A significant difference between groups in spectral peak location was observed for both the chronological age comparison ($X^2[1] = 4.90$, $p = 0.039$) and the hearing age comparison ($X^2[1] = 10.32$, $p < 0.002$). The spectral peak locations of the children with CIs were lower than those of both groups of children with NH.

The consonant by group interaction was significant for both models: the one for the chronological age comparison ($X^2[1] = 39.75$, $p < 0.001$) and the one for the hearing age comparison ($X^2[1] = 10.79$, $p = 0.004$). The children with CIs produced less difference between the spectral peaks of /s/ and /ʃ/ than either group of children with NH. It can be seen in Fig. 1 that for the chronological age comparison this interaction was due to the spectral peaks of productions of /s/ by the children with CIs being lower than those of the children with NH while productions of /ʃ/ were similar between the groups. This same pattern is less apparent in Fig. 2 for the hearing age comparison, since spectral peaks of both /s/ and /ʃ/ appear somewhat lower for the children with CIs.

To investigate whether there was a significant difference between groups in spectral peak location for both /s/ and /ʃ/, likelihood ratio tests were performed to investigate the effect of group on spectral peaks for /s/ and on spectral peaks for /ʃ/, separately. For productions of /s/, a significant effect of group was found when the productions of the children with CIs were compared to either group of children with NH (chronological age comparison: $X^2[1] = 16.43$, $p = 0.001$; hearing age comparison: $X^2[1] = 13.66$, $p < 0.001$) with the children with CIs producing /s/ with lower spectral peaks than the children with NH. For productions of /ʃ/, a significant effect of group was not found when the productions of the children with CIs were compared to those of the children with NH in the chronological age comparison ($X^2[1] = .37$, $p = 0.536$) or to those of the children with NH in the hearing age comparison ($X^2[1] = 2.76$, $p > 0.104$).

It is possible that group differences in spectral peak locations for /s/ between the children with CIs and the children with NH in the hearing age comparison may have been due,

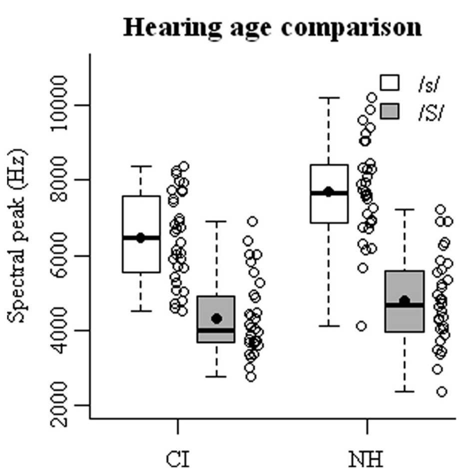

FIG. 2. Boxplots representing the range of the participants' mean spectral peaks of productions of /s/ and /ʃ/ by the children with cochlear implants (CI; n = 32) and the normally hearing children (NH; n = 32) in the hearing age comparison group. Horizontal bars represent the median. Whiskers extend to the farthest data points. Data points are shown to the right of the box plots. Group means are shown by the black points.

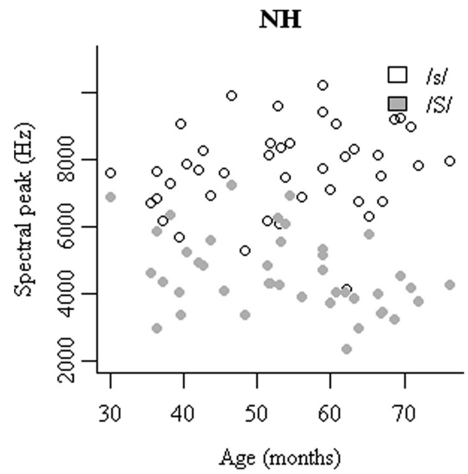

FIG. 3. Scatterplot representing the relationship between age and mean spectral peaks for /s/ (white) and /ʃ/ (gray) by the normally hearing children (n = 42).

at least in part, to vocal tract size differences between these two groups of children. The children with CIs were on average 1.5 years older than the children with NH. It is to be expected that children who are older have larger vocal tracts and lower spectral peaks. The effect of vocal tract size on spectral peak locations was investigated by examining the relationship between age and spectral peaks for the children with NH (n = 42; age range = 30 to 76 months), and for the children with CIs (n = 32; age range = 49 to 92 months), separately. One child in each group was left out of the analysis, because their ages were too far (at least 16 months) from those of the other children in the group. Figures 3 and 4 show the relationship between age and peak location for /s/ and /ʃ/ for the children with NH and the children with CIs, respectively. For both groups, the effect of age on spectral peak location of productions of /s/ and /ʃ/ was not significant (CI: $X^2[1] = 3.44$, $p = 0.068$; NH: $X^2[1] = 1.09$, $p = 0.28$), but the effect of age reached significance on spectral means of productions of /s/ and /ʃ/ for the children with NH ($X^2[1] = 4.16$, $p = 0.04$). The interaction between age and consonant on spectral peaks was significant for the children with NH ($X^2[1] = 17.43$, $p < 0.001$), but was not significant for the children with CIs ($X^2[1] = 2.00$, $p = 0.156$). However, there was

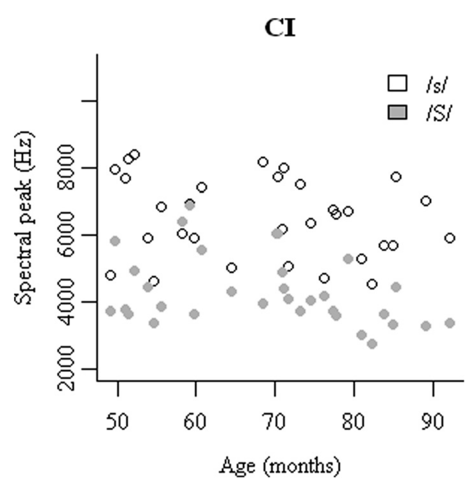

FIG. 4. Scatterplot representing the relationship between age and mean spectral peaks for /s/ (white) and /ʃ/ (gray) by the children with CIs (n = 32).

a marginally significant interaction between age and consonant on spectral means for the children with CIs ($X^2[1] = 3.86$, $p = 0.056$). When examining the effect of age on spectral peaks for productions of /s/ and /ʃ/ separately, it was found that for both groups, the effect of age on spectral peaks was significant for /ʃ/ (CI: $X^2[1] = 4.57$, $p = 0.029$; NH: $X^2[1] = 6.83$, $p = 0.014$), but the effect of age on spectral peaks was not significant for /s/ (CI: $X^2[1] = 0.91$, $p > 0.339$; NH: $X^2[1] = 1.12$, $p > 0.289$). That is, the peak location of /ʃ/ decreased significantly as age increased, but no such relationship was found between age and peak location for /s/. This same pattern was true for the effect of age on spectral means of productions of each of /s/ and /ʃ/ by the children with NH, but the effect of age on spectral means of productions of /ʃ/ failed to reach significance for the children with CIs ($X^2[1] = 3.39$, $p = 0.082$). The difference in production of /s/ between the children with CIs and the children with NH in the hearing age comparison group is unlikely to be due to differences in vocal tract size, as there was not a significant effect of age on spectral peaks for productions of /s/ for either the children with CIs or the children with NH.

C. Results of the simulation of electrode output of /s/ and /ʃ/

Figure 5 shows the root-mean-square energy in dB of each channel of the simulated CI processing of productions of /s/ and /ʃ/ by a six year old female with NH. Each of the two productions of each fricative was produced with a different following vowel. The spectral peak locations and spectral means of the original fricative signals were 9410 Hz and 8575 Hz for /se/, 5727 Hz and 6702 Hz for /sɪ/, 3919 Hz and 5995 Hz for /ʃi/, and 2627 Hz and 4732 Hz for /ʃu/, respectively.

As can be seen in Fig. 5, the productions of /s/ and /ʃ/ both increase in level as channel number increases. However, the energy of the productions of /s/ is lower in channel 6 (2005 to 3181 Hz) and 7 (3181 to 5044 Hz) than is that of /ʃ/. This is especially true for one of the productions of /s/. The other production of /s/ has energy levels that are more similar to that of the /ʃ/ productions. This suggests that children with CIs may be able to discriminate between /s/ and /ʃ/ by noticing the higher energy levels at mid-upper channels for /ʃ/ which gives /ʃ/ lower-frequency spectral energy and a broader spectral shape. However, discrimination between these sounds could be more or less difficult depending on the level of the energy of /s/ at the mid-upper channels.

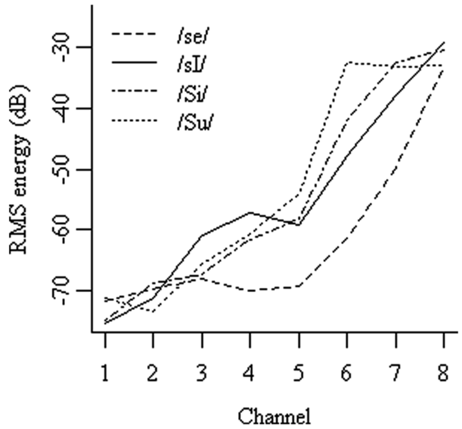

FIG. 5. Simulated cochlear implant channel output for two [s] and two [ʃ] produced by a six year old female. Higher channels represent frequency bands of higher frequencies. The fricative (/s/ or /ʃ/) and the vowel sound that followed (/i/, /I/, /u/, or /e/) are indicated by the line type.

IV. DISCUSSION

The aim of this study was to determine whether children with CIs produce less contrast between /s/ and /ʃ/ than children with NH. Productions of /s/ and /ʃ/ by children with CIs were compared to those of two comparison groups: children with NH of the same chronological age as the children with CIs and children with NH of the same hearing age. This study differed from previous studies in that only productions transcribed as correct were included in the analysis of acoustic contrast.

The results of the transcription analysis showed that /s/ was produced with lower accuracy than /ʃ/ by all of the groups, which suggests that it is more difficult for children to make correct /s/ production than /ʃ/ productions when fairly broad criteria are used to judge productions as incorrect as was done in this study i.e., when even distortions are considered incorrect. The results of the transcription analysis furthermore showed that the children with CIs produced /s/ and /ʃ/ with a level of accuracy that was more similar to that of their hearing-age peers than to that of their chronological-age peers (although group differences were not significant). The levels of accuracy that the children with CIs showed should be interpreted carefully, however, because of the type of task used in this study to elicit the productions of /s/ and /ʃ/. The low accuracy of the children with CIs may have been due in part to the perceptual component of the word elicitation task which required the children to repeat each word after an auditory prompt. A different type of elicitation task such as picture-naming, with fewer perceptual demands, may have resulted in higher accuracy scores for the children with CIs. Furthermore, the word elicitation task that was used may have aided the performance of the children with NH since it presented them with an adult model.

The different error patterns for the two groups support the claim that the children with CIs had perceptual difficulties with the elicitation task. The errors that the children with CIs produced for /s/ were different from those of the children with NH. The children with CIs produced many [f] for /s/ substitutions while there were almost no [f] for /s/ substitutions by the children with NH. A substitution of [f] for /s/ is not a typical developmental sound substitution (Smit, 1993). Furthermore, previous studies have shown that /s/ is a difficult sound for individuals with CIs to identify and that /s/ is often confused with /f/ (Munson *et al.*, 2003; Donaldson and Kreft, 2006; Giezen *et al.*, 2010). The spectral energy of /f/ is relatively flat compared to that of /s/. The perceptual confusion of /s/ with /f/ by individuals with CIs may be related to the finding that /s/ can be heard by NH individuals as /f/ or /θ/ when it is low-pass filtered (Stelmachowicz *et al.*, 2001) which suggests that when listeners do not hear that there is a high frequency spectral peak, listeners perceive /s/

as /f/. Perhaps due to broad current spread of electrodes (Friesen *et al.*, 2001) and an upper frequency limit that is lower than that of individuals with NH, individuals with CIs may not hear that /s/ has a high frequency spectral peak in some cases. This may happen more for speakers who produce higher frequency spectral peaks such as female speakers (e.g., Stelmachowicz *et al.*, 2008). That an adult female produced the auditory stimuli in this study may have contributed to a perceptual confusion of /f/ for /s/.

While a visual prompt was included to support each auditory prompt, the pictures used were not always explicit due to the abstract nature of some of the stimulus words (e.g., *super*). Therefore, the visual prompts might not have compensated for inaccurate perception of the auditory stimuli. The errors the children produced for /ʃ/ were similar across the groups. Therefore, perhaps the results of the accuracy analysis and error analysis for /ʃ/ were less affected by perceptual errors than they may have been for /s/. This is consistent with the finding that it is typically easier for individuals with CIs to identify /ʃ/ than /s/ (Donaldson and Kreft, 2006; Lane *et al.*, 2007b).

The errors that the children produced for /s/ and /ʃ/ did not affect the results of the spectral analysis since that analysis included only productions that were transcribed as correct. The spectral analysis revealed that the children with CIs produced less contrast between /s/ and /ʃ/ than either group of children with NH. This result is consistent with the findings of other studies (Uchanski and Geers, 2003; Liker *et al.*, 2007; Mildner and Liker, 2008), but shows in addition, that children with CIs produced reduced contrast between /s/ and /ʃ/ even for correct productions. This finding indicates that while productions of these sounds by a child with CIs may be perceived as accurate, they likely differ from the productions of children with NH at a subphonemic level. Furthermore, the fact that the children with CIs showed reduced contrast between /s/ and /ʃ/ compared to children with NH with the same hearing age suggests that children with CIs produce less contrast between /s/ and /ʃ/ than children with NH with the same chronological age for reasons other than having less auditory exposure. It may be that children with CIs produce less contrast between /s/ and /ʃ/ than children with NH because of limitations in auditory discrimination or because children with CIs acquire this contrast more slowly than children with NH.

The pattern of results was that the children with CIs produced /s/ with spectral peaks that were lower in frequency than those of the children with NH, but the spectral peaks of productions of /ʃ/ were similar across the groups. Since the children with CIs were older than the children with NH in the hearing age comparison, it was worth investigating whether the difference in /s/ production between the children with CIs and these children with NH was due to differences in vocal tract size. Previous studies have found that children produce fricatives at higher frequencies than adults (Nittrouer, 1995; Fox and Nissen, 2005). This is consistent with the fact that children have smaller vocal tracts than adults, and therefore their fricative productions resonate at higher frequencies. In this study, a significant negative relationship between age and spectral peak location was found for /ʃ/ for both the children with CIs and the children with NH, but a significant relationship between spectral peak location and age was not found for /s/. This result supports the claim that the children with CIs produced /s/ with lower spectral peaks than the children with NH in the hearing age comparison because of differences in auditory perceptual abilities rather than differences in vocal tract size. The difference in the effect of age on spectral peaks of productions of /s/ and /ʃ/ is consistent with results of Fox and Nissen (2005) who found that over a much larger age range, age explained more of the variability in spectral peak locations of /ʃ/ than of /s/.

Uchanski and Geers (2003) and Liker *et al.* (2007) similarly noted that children with CIs produced reduced contrast between /s/ and /ʃ/ due to the production of /s/ at lower frequencies. There are different possible explanations for this finding. First, /s/ has energy at higher frequencies than /ʃ/, and CIs deliver poorer frequency resolution for the higher frequencies. Therefore, the children with CIs may have produced /s/ at lower frequencies, because within category discrimination of /s/ is more difficult than within category discrimination of /ʃ/.

However, the difference between the two productions of /s/ that were processed to simulate the processing of a CI (Fig. 5), suggests that children with CIs may be able to discriminate some productions of /s/ by noticing differences in general spectral shape and differences in channel output level at a number of channels. Examination of whether providing higher spectral resolution at high frequencies gives listeners better within-category discrimination of /s/ could help to clarify whether this is a likely explanation. Second, children with CIs may produce /s/ at lower frequencies so that more of the energy of their productions of /s/ is at frequencies that are within the range of frequencies that they can hear. Figures 1 and 2 show that it is not uncommon for children with NH to produce /s/ with spectral peaks above 8 kHz, the upper frequency limit of the CIs of most of the children in this study. If this is the reason the children with CIs produced lower frequency productions of /s/, then the reduced contrast that they produced between /s/ and /ʃ/ may be less because of limitations in discrimination, and rather, because of an upper frequency limit that is different from that of the children with NH.

The finding that children with CIs produce less contrast between /s/ and /ʃ/ than children with NH has two implications. First, reduced contrast may explain in part why the speech of children with CIs is less intelligible than that of their peers with NH. Further research is needed to determine whether listeners respond negatively to the reduced contrast that children with CIs produce between /s/ and /ʃ/. While listeners may accurately distinguish productions of /s/ and /ʃ/ by children with CIs, the speed or ease with which listeners distinguish these productions may be reduced (Newman *et al.*, 2001). Second, this finding may support the hypothesis that production of contrast is related to auditory discrimination ability (Perkell *et al.*, 2004). Support for this hypothesis would be strengthened if future research finds that as children with CIs develop, they continue to produce less contrast between /s/ and /ʃ/ than their peers with NH and if future research finds that children with CIs produce reduced contrast between phoneme contrasts other than /s/ and /ʃ/.

ACKNOWLEDGMENTS

This work is supported by NIH Grant No. R01DC008365 to R.Y.L. and NIH Grant No. R01DC02932 and NSF Grant No. BCS-0729140 to J.R.E. The authors thank Marios Fourakis for his help with interpretation of the results, Matthew Goupell for designing the CI simulation, and also Shelly Godar, Emilie Sweet, Cynthia Zettler, Sarah Schellinger, and Ryan Sovinski for their assistance with data collection and analysis. Finally, the authors are most grateful to the parents who gave their consent and to the children who participated in this study.

[1]In the study by Uchanski and Geers (2003), only productions that maintained the fricative feature were included in the acoustic analysis. In the studies by Mildner and Liker, (2008) and Liker, Mildner, and Sindija (2007) there is no mention of exclusion of any tokens from the acoustic analysis.

Baayen, R. H., Davidson, D. J., Bates, D. M. (**2008**). "Mixed-effects modeling with crossed random effects for subjects and items," J. Mem. Lang. **59**, 390–412.

Blacklock, O. S. (**2004**). "Characteristics of variation in production of normal and disordered fricatives, using reduced-variance spectral methods," Ph.D. thesis, University of Southampton, Southampton, UK.

Blamey, P., Barry, J. G., and Jacq, P. (**2001**). "Phonetic inventory development in young cochlear implant users 6 years postoperation," J. Speech Lang. Hear. Res. **44**, 73–79.

Boothroyd, A., and Medwetsky, L. (**1992**). "Spectral distribution of /s/ and the frequency response of hearing aids," Ear Hear. **13**, 150–157.

Brownell, R., ed. (**2000**). *Receptive One-Word Picture Vocabulary Test*, 2nd ed. (Academic Therapy Publication, Inc, Novato, CA), pp. 1–110.

Burgemeister, B. B., Blum, L. H., and Lorge, I. (**1972**). *Columbia Mental Maturity Scale*, 3rd ed. (Harcourt, Brace, Jovanovich, New York), pp. 1–63.

Chin, S. B., Tsai, P. L., and Gao, S. (**2003**). "Connected speech intelligibility of children with cochlear implants and children with normal hearing," Am. J. Speech Lang. Pathol. **12**, 440–451.

Donaldson, G. S., and Kreft, H. A. (**2006**). "Effects of vowel context on the recognition of initial and medial consonants by cochlear implant users," Ear Hear. **27**, 658–677.

Dorman, M. F., Loizou, P. C., Kemp, L. L., and Kirk, K. I. (**2000**). "Word recognition by children listening to speech processed into a small number of channels: Data from normal-hearing children and children with cochlear implants," Ear Hear. **21**, 590–596.

Dorman, M. F., Soli, S., Dankowski, K., Smith, L. M., McCandless, G., and Parkin, J. (**1990**). "Acoustic cues for the consonant identification by patients who use the Ineraid cochlear implant," J. Acoust. Soc. Am. **88**, 2074–2079.

Edwards, J., and Beckman, M. E. (**2008**). "Some cross-linguistic evidence for modulation of implicational universals by language-specific frequency effects in phonological development," Lang. Learn. Dev. **4**, 122–156.

Eisenberg, L. S., Martinez, A. S., and Boothroyd, A. (**2003**). "Auditory-visual and auditory-only perception of phonetic contrasts in children," Volta Rev. **103**, 327–346.

Eisenberg, L. S., Shannon, R. V., Martinez, A. S., Wygonski, J., and Boothroyd, A. (**2000**). "Speech recognition with reduced spectral cues as a function of age," J. Acoust. Soc. Am. **107**, 2704–2710.

Flipsen, P., Jr., and Colvard, L. G. (**2006**). "Intelligibility of conversational speech produced by children with cochlear implants," J. Comm. Disord. **39**, 93–108.

Forrest, K., Weismer, G., Milenkovic, P., and Dougall, R. N. (**1988**). "Statistical analysis of word-initial voiceless obstruents: Preliminary data," J. Acoust. Soc. Am. **84**, 115–123.

Fox, R. A., and Nissen, S. L. (**2005**). "Sex-related acoustic changes in voiceless English fricatives," J. Speech Lang. Hear. Res. **48**, 753–765.

Friesen, L. M., Shannon, R. V., Baskent, D., and Wang, X. (**2001**). "Speech recognition in noise as a function of the number of spectral channels: Comparison of acoustic hearing and cochlear implants," J. Acoust. Soc. Am. **110**, 1150–1163.

Giezen, M. R., Escudero, P., and Baker A. (**2010**). "Use of acoustic cues by children with cochlear implants," J. Speech Lang. Hear. Res. **53**, 1440–1457.

Goldman, R., and Fristoe, M. (**2000**). *The Goldman-Fristoe Test of Articulation 2* (American Guidance Service, Inc., Circle Pines, MN), pp. 1–146.

Grieco-Calub, T. M., Saffran, J. R., and Litovsky, R. Y. (**2009**). "Spoken word recognition in toddlers who use cochlear implants," J. Speech Lang. Hear. Res. **52**, 1390–1400.

Hedrick, M. S., and Ohde, R. N. (**1993**). "Effect of relative amplitude of frication on perception of place of articulation," J. Acoust. Soc. Am. **94**, 2005–2026.

Jaeger, T. F. (**2008**). "Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models," J. Mem. Lang. **59**, 434–446.

Jongman, A., Wayland, R., and Wong, S. (**2000**). "Acoustic characteristics of English fricatives," J. Acoust. Soc. Am. **108**, 1252–1263.

Kishon-Rabin, L., Taitelbaum, R., Muchnik, C., Gehtler, I., Kronenberg, J., and Hildesheimer, M. (**2002**). "Development of speech perception and production in children with cochlear implants," Ann. Otol. Rhinol. Laryngol. **111**, 85–90.

Lane, H., Denny, M., Guenther, F. H., Hanson, H. M., Marrone, N., Matthies, M. L., Perkell, J. S., Stockman, E., Tiede, M., Vick, J., and Zandipour, M. (**2007a**). "On the structure of phoneme categories in listeners with cochlear implants," J. Speech Lang. Hear. Res. **50**, 2–14.

Lane, H., Matthies, M. L., Guenther, F. H., Denny, M., Perkell, J. S., Stockmann, E., Tiede, M., Vick, J., and Zandipour, M. (**2007b**). "Effects of short-and long-term changes in auditory feedback on vowel and sibilant contrasts," J. Speech Lang. Hear. Res. **50**, 913–927.

Li, F., Edwards, J., and Beckman, M. E. (**2009**). "Contrast and covert contrast: The phonetic development of voiceless sibilant fricatives in English and Japanese toddlers," J. Phonetics **37**, 111–124.

Liker, M., Mildner, V., and Sindija, B. (**2007**). "Acoustic analysis of the speech of children with cochlear implants: A longitudinal study," Clin. Linguist. Phonetics **21**, 1–11.

Matthies, M. L., Svirsky, M. A., Lane, H. L., and Perkell, J. S. (**1994**). "A preliminary study of the effects of cochlear implants on the production of sibilants," J. Acoust. Soc. Am. **96**, 1367–1373.

Mildner, V., and Liker, M. (**2008**). "Fricatives, affricates, and vowels in Croatian children with cochlear implants," Clin. Linguist. Phon. **22**, 845–856.

Munson, B., Donaldson, G. S., Allen, S. L., Collison, E. A., and Nelson, D. A. (**2003**). "Patterns of phoneme perception errors by listeners with cochlear implants as a function of overall speech perception ability," J. Acoust. Soc. Am. **113**, 925–935.

Newman, R. S., Clouse, S. A., and Burnham, J. L. (**2001**). "The perceptual consequences of within-talker variability in fricative production," J. Acoust. Soc. Am. **109**, 1181–1196.

Nissen, S. L., and Fox, R. A. (**2005**). "Acoustic and spectral characteristics of young children's fricative productions: A developmental perspective," J. Acoust. Soc. Am. **118**, 2570–2578.

Nittrouer, S. (**1995**). "Children learn separate aspects of speech production at different rates: Evidence from spectral moments," J. Acoust. Soc. Am. **97**, 520–530.

Nittrouer, S., Studdert-Kennedy, M., and McGowan, R. S. (**1989**). "The emergence of phonetic segments: Evidence from the spectral structure of fricative-vowel syllables spoken by children and adults," J. Speech Hear. Res. **32**, 120–132.

Peng, S., Spencer, L. J., and Tomblin, J. B. (**2004**). "Speech intelligibility of pediatric cochlear implant recipients with 7 years of device experience," J. Speech Lang. Hear. Res. **47**, 1227–1236.

Percival, D. B., and Walden, A. T. (**1993**). *Spectral Analysis for Physical Applications: Multitaper and Conventional Univariate Techniques* (Cambridge University Press, Cambridge), pp. 1–583.

Perkell, J. S., Matthies, M. L., Tiede, M., Lane, H., Zandipour, M., Marrone, N., Stockmann, E., and Guenther, F. H. (**2004**). "The distinctness of speakers' /s/ - /ʃ/ contrast is related to their auditory discrimination and use of an articulatory saturation effect," J. Speech Lang. Hear. Res. **47**, 1259–1269.

Shannon, R. V. (**2002**). "The relative importance of amplitude, temporal, and spectral cues for cochlear implant processor design," Am. J. Audiol. **11**, 124–127.

Smit, A. B. (**1993**). "Phonologic error distributions in the Iowa-Nebraska articulation norms project: Consonant singletons," J. Speech Hear. Res. **36**, 533–547.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., and Lewis, D. E. (**2001**). "Effect of stimulus bandwidth on the perception of /s/ in normal-and hearing-impaired children and adults," J. Acoust. Soc. Am. **110**, 2183–2190.

Stelmachowicz, P. G., Nishi, K., Choi, S., Lewis, D. E., Hoover, B. M., and Dierking, D. (**2008**). "Effects of stimulus bandwidth on the imitation of English fricatives by normal-hearing children," J. Speech Lang. Hear. Res., **51**, 1369–1380.

Stevens, K. N. (**2000**). *Acoustic Phonetics* (The MIT Press, Cambridge), pp. 1–607.

Summerfield, Q. A., Nakisa, M. J., McCormick, B., Archbold, S., Gibbin, K. P., and O'Donoghue, G. M. (**2002**). "Use of vocalic information in the identification of /s/ and /ʃ/ by children with cochlear implants," Ear Hear. **23**, 58–77.

Tobey, E. A., Wiessner, N., Lane, J., Sundarrajan, M., Buckley, K. A., and Sullivan, J. (**2007**). "Phoneme accuracy as a function of mode of communication in pediatric cochlear implantation," Audiolog. Med. **5**, 283–292.

Tomblin, J. B., Peng, S., Spencer, L. J., and Lu, N. (**2008**). "Long-Term trajectories of the development of speech sound production in pediatric cochlear implant recipients," J. Speech Lang. Hear. Res. **51**, 1353–1368.

Uchanski, R. M., and Geers, A. W. (**2003**). "Acoustic characteristics of the speech of young cochlear implant users: A comparison with normal-hearing age-mates," Ear Hear. **24**, 90S–105S.

Williams, K. T. (**1997**). *Expressive Vocabulary Test* (American Guidance Service, Inc, Circle Pines, MN), pp. 1–176.