

Title:

Production of contrast between sibilant fricatives by children with cochlear implants^{a)}

Authors:

Ann E. Todd

Jan R. Edwards^{b)}

Ruth Y. Litovsky

University of Wisconsin Waisman Center, 1500 Highland Ave, and Department of
Communicative Disorders, Madison, Wisconsin 53705

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^{b)} Author to whom correspondence should be addressed. Electronic mail:

jedwards2@wisc.edu

ABSTRACT

Speech production by children with cochlear implants (CIs) is generally less intelligible and less accurate than that of normally hearing children. Research has also reported that children with CIs produce less acoustic contrast between phonemes than normally hearing children, but these studies have included both 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 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, due to production of /s/ with lower spectral peaks. The children with CIs produced contrast between /s/ and /ʃ/ that was similar to that of the normally hearing children with the same duration of auditory experience. The results indicate that there may be differences between the productions of children with CIs and their normally hearing peers, even for sounds that adults transcribe as correct.

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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, Tsai, & Goa, 2003; Peng, Spencer, & Tomblin, 2004) or how accurately they produce phonemes (e.g., Blamey, Barry, & Jacq, 2001; Tobey et al., 2007; Tomblin, Peng, Spencer, & Lu, 2008). While these studies have generally observed that children with CIs have poorer speech production than their normally hearing (NH) peers, 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 NH children on a subphonemic level. For example, the speech of children with CIs could differ in production of contrast between phonemes. The present study investigated whether children with CIs produce less contrast between the fricatives /s/ and /ʃ/ than NH children.

There are two possible reasons why children with CIs might produce less contrast between /s/ and /ʃ/ than NH children. First, in children with NH, there is a protracted period of acquisition of the contrast between /s/ and /ʃ/ (Nittrouer, Studdert-Kennedy, & McGowan, 1989; Nittrouer, 1995; Nissen & Fox, 2005; Li, Edwards, & Beckman, 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 NH children of the same age because they go through a period of auditory deprivation before receiving a CI. Second, this contrast may be particularly difficult for children with CIs because of its relationship to auditory discrimination ability (Perkell, Matthies et al., 2004). Children with CIs have poor auditory discrimination and may have particular difficulty with /s/ because its fricative spectrum is high in

frequency and cochlear implants generally provide poorer frequency resolution for higher frequencies.

Findings from studies in which the speech of children with CIs has been analyzed acoustically have shown that when attempting to produce /s/ and /ʃ/ these children produce less contrast than NH children (Uchanski & Geers, 2003; Milder & Liker, 2008; Liker, Mildner, & Sindija, 2007). In these studies, all productions of target /s/ and /ʃ/ were included in the acoustic analyses as long as the attempts were fricatives¹. Children with CIs in general have low accuracy for the production of /s/ (Blamey, Barry, & Jacq, 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 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 of children with CIs to that of NH children of the same hearing age as the children with CIs in addition to comparing the children with CIs to NH children of the same chronological age. A child's hearing age is the amount of time that child has been with auditory stimulation, and in this study was defined for the children with CIs as the time since activation of the first CI (Flipsen & 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 NH children 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.

II. METHOD

A. Participants

Participants were children between the ages of 4 to 9 years who use CIs ($n = 33$) and children with normal hearing 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, WI, 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 his/her child used total communication. Characteristics of the children with CIs are shown in Table I. Recordings from 5 children with CIs were not included due to either errors made in the recording procedure ($n = 3$), lack of cooperation during the recording procedure ($n = 1$), or a possible diagnosis of pervasive developmental disorder ($n = 1$).

Data for two of the NH children were obtained in Madison, WI under circumstances identical to those under which children with CIs were tested. The remainder of that data set was from a database of audio recordings of children's speech production (Edwards & Beckman, 2008b). 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, OH, where the recordings were made. All NH children 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 NH children scored lower

than one standard deviation below the mean on norm-referenced tests of articulation (Goldman & Fristoe, 2000), receptive vocabulary (Brownell, 2000), expressive vocabulary (Williams, 1997), or non-verbal IQ (Burgemeister, Blum, & Lorge, 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 NH children.

The children with CIs and the NH children were English speakers. Any child who never produced /s/ or /ʃ/ correctly during the speech elicitation task was excluded from the analysis.

Three children with CIs were excluded for this reason.

Twenty-one of the 33 children with CIs were compared to NH children 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 NH children matched to the children with CIs on hearing age (within four months) and sex (for 28 of 33 children). The hearing age of each child with CIs was calculated by subtracting the age at which the child's first cochlear implant was activated from the child's chronological age. Not every child with CIs was included in each comparison due to the inability to match NH children 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, which included 9 words with /s/ in the initial position and 9 words with /ʃ/ in the initial position. Following /s/ and /ʃ/ was a vowel from one of three vowel categories (approximately /i/, /a/, /u/) which were

distributed evenly throughout the stimuli. Vowels producing similar coarticulatory effects were grouped together in the same category. That is, /ɑ/, /ʌ/, and /ɔ/ were in the same category; /i/ and /I/ 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.

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. Multiple tokens of each word were recorded. Only those tokens that were perceived correctly by at least 80% of adult native English speakers were included in the study. Visual stimuli were color photographs that corresponded to the auditory stimuli e.g., for the auditory stimulus “sister” there was a photograph of two similar-looking girls. The order of the stimuli was randomized.

C. Procedure

The children with CIs and the NH children who participated in WI were recorded in a sound-attenuated booth, while the NH children who participated in OH were recorded in a quiet room at their school or daycare center. The target words were elicited by a picture-prompted auditory repetition task. The children were provided with 10 practice trials consisting of words beginning with various sounds. A single production of each word was elicited unless the child said the wrong word or the child’s production was difficult to hear. 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 NH children 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 three error types in the case of incorrect productions, and wrote the substituted sound in the case of substitution errors.

Inter-transcriber reliability was calculated separately for the children with CIs and the NH children using 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.

E. Psychoacoustic Analysis

A psychoacoustic scale was used for the analysis of correctly-transcribed productions of /s/ and /ʃ/. For each production, 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. The middle 40 ms of the fricatives were extracted using a Hamming window. The number of sones present in each of the frequency bands corresponding to bands 6 to 42 on the ERB scale (Glasberg & Moore, 1990) was calculated, and the band with the highest loudness was noted. In this study, the band with the highest loudness is referred to as the *peak ERB*. The peak ERB is the psychoacoustic analog to the peak of a linear spectrum which has been shown to differentiate /s/ and /ʃ/ (Jongman, Wayland, & Wong, 2000). The psychoacoustic measure of peak ERB was used, because psychoacoustic measures are based on the human auditory system. Therefore, differences between groups found with peak ERB are more likely to be differences to which listeners are sensitive than differences found with an acoustic measure.

III. RESULTS

A. Transcription

Two-way ANOVAs with consonant (/s/ vs. /ʃ/) as a within-subjects factor and group (CI vs. NH) as a between-subjects factor were used to analyze the accuracy results for the chronological age comparison and the hearing age comparison. For the chronological age comparison, the effects of consonant ($F[1,40] = 16.67, p < .001$, partial $\eta^2 = .294$) and group ($F[1,40] = 11.72, p = .001$, partial $\eta^2 = .227$) were significant, but the interaction between consonant and group ($F[1,40] = 0.0008, p = .98$) was not significant. The mean percent of /s/ and /ʃ/ productions by the children with CIs that were transcribed as correct was 55.8 (SD = 22.2) and 75.0 (SD = 26.2), respectively, which was lower than that of the NH children whose mean accuracy was 72.8 (SD = 25.4) for

/s/ and 92.2 (SD = 12.2) for /ʃ/. Both groups produced /ʃ/ more accurately than /s/.

For the hearing age comparison, the effect of consonant was significant ($F[1,62] = 24.79, p < .001, \text{partial } \eta^2 = .286$), but the effect of group ($F[1,62] = .58, p = .45$) and the consonant by group interaction ($F[1,62] = .45, p = .50$) were not significant. The mean percent-correct /s/ and /ʃ/ productions for the children with CIs was 62.0 (SD = 24.5) and 82.5 (SD = 23.7), respectively, which was similar to that of the NH children whose mean percent-correct was 67.8 (SD = 23.5) for /s/ and 83.4 (SD = 19.9) for /ʃ/. Again, both groups produced /ʃ/ more accurately than /s/. It must be kept in mind that 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 and V show the most frequent errors produced for /s/ and /ʃ/. The errors that the children with CIs produced differed from the errors of the NH children 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 produced /f, θ/ or a stop. When the NH children produced /s/ incorrectly, they most frequently produced /ʃ, θ, ts/. Both groups of children produced /tʃ, s/ as the most frequent errors when the target sound was /ʃ/. This pattern was true for the chronological age comparison and the hearing age comparison.

B. Psychoacoustic Analysis

The effects of consonant (/s/ vs. /ʃ/), group (CI vs. NH), and the interaction between consonant and group on peak ERB were tested using likelihood ratio tests on linear mixed-effects models (e.g., see Baayen, Dixon, & Bates, 2008) that included participants as a random effect. The test statistic of each likelihood ratio was analyzed using a 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.

Figures 1 and 2 show the mean peak ERBs of productions of /s/ and /ʃ/ by the children in the chronological age comparison and the children in the hearing age comparison, respectively. For both comparisons, mean peak ERBs of /s/ were higher than mean peak ERBs of /ʃ/. This was confirmed by the statistical analysis: the effect of consonant was significant for the chronological age comparison ($X^2[1] = 311.87, p < .001$) and the hearing age comparison ($X^2[1] = 413.15, p < .001$).

A significant difference between groups was found for the hearing age comparison ($X^2[1] = 11.47, p = .001$). This is evident in Figure 2, where the mean peak ERBs of productions of /s/ and /ʃ/ by the children with CIs were lower than those of the NH children. The effect of group was only marginally significant for the chronological age comparison ($X^2[1] = 3.91, p = .058$).

The consonant by group interaction was significant for both the chronological age comparison ($X^2[1] = 24.36, p < .001$) and the hearing age comparison ($X^2[1] = 4.98, p = .025$) with the children with CIs producing less contrast between /s/ and /ʃ/ than the NH

children. As observed in Figure 1 for the chronological age comparison, the mean peak ERBs of productions of /s/ by the children with CIs were lower than those of the NH children. In Figure 2, it can be observed that this result is much less apparent for the hearing age comparison.

IV. DISCUSSION

The aim of this study was to determine whether children with CIs produce less contrast between /s/ and /ʃ/ than NH children. Productions of /s/ and /ʃ/ by children with CIs were compared to those of both NH children matched to the children with CIs on chronological age and NH children matched to the children with CIs on hearing age. Only productions transcribed as correct were included in the analysis of 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. The results of the transcription analysis furthermore showed that the children with CIs produced /s/ and /ʃ/ less accurately than NH of the same chronological age, but with accuracy similar to that of NH of the same hearing age. These accuracy results 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.

The different error patterns for the two groups support this 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 NH children. The children with CIs produced many /f/ for /s/ substitutions while there were almost no /f/ for /s/ substitutions by the NH children. A substitution of /f/ for /s/ is not a typical developmental sound substitution (Smit, 1993). Other research suggests that /s/ is a particularly difficult sound for individuals with CIs to perceive (Munson, Donaldson, Allen, Collison, & Nelson, 2003). 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, and 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 & Kreft, 2006).

The errors that the children produced for /s/ and /ʃ/ did not affect the results of the psychoacoustic analysis since that analysis included only productions that were transcribed as correct. The psychoacoustic analysis showed that the children with CIs produced /s/ and /ʃ/ with lower peak ERBs than their NH hearing-age peers. This difference between groups may have been due to differences in hearing status; however,

an alternative explanation is that it was due to differences in vocal tract size. The children with CIs were on average about 1.5 years older than the NH in the hearing age comparison. As a group, the children with CIs probably had larger vocal tracts which could have caused productions of /s/ and /ʃ/ to resonate at lower frequencies. This group difference was only marginally significant when the children with CIs were compared to NH children of the same chronological age.

The psychoacoustic analysis showed that the children with CIs produced less contrast between /s/ and /ʃ/ than the NH in the chronological age comparison. This result is consistent with the findings of other studies (Uchanski & Geers, 2003; Liker et al., 2007; Mildner & 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 the production of these sounds by a child with CIs may be perceived as accurate, they likely differ from the productions of NH children on a subphonemic level. Future research is needed to explore whether listeners respond differently to the productions of /s/ and /ʃ/ by children with CIs than to the productions of /s/ and /ʃ/ by NH children. 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, Clouse, & Burnham, 2001).

When the children with CIs were compared to NH children of the same hearing age, there was much less difference in the production of contrast between /s/ and /ʃ/ between the groups. This may indicate that children with CIs produce less contrast between /s/ and /ʃ/ than their chronological-age peers because they have had less auditory exposure (i.e., have younger hearing

ages). However, future research is needed to know if these children will continue to develop this contrast along with their hearing-age peers, or if they will continue to produce reduced contrast between /s/ and /ʃ/ due to limited auditory perceptual abilities. The pattern of production of /s/ and /ʃ/ by the children with CIs suggests that poor auditory discrimination ability may be responsible for the reduced contrast produced by the children with CIs. The children with CIs produced /s/ with peak ERBs that were lower than those by the NH children in the chronological age comparison, but the peak ERBs of productions of /ʃ/ appeared similar across the groups. Uchanski and Geers (2003) and Liker et al. (2007) noted similar observations. Because /s/ is higher in frequency than /ʃ/ and the filters of CIs are wider in the higher frequencies, individuals who use CIs receive poorer frequency resolution for /s/ than for /ʃ/. Therefore, it is not surprising that the children with CIs produced /s/ more differently from the productions by their NH chronological-age peers than /ʃ/. The children with CIs may have produced /s/ with lower peak ERBs, because they could not perceive the distinction between a higher frequency /s/ and a lower frequency /ʃ/, or because they were attempting to produce /s/ at lower frequencies where they have better frequency resolution.

The finding that children with CIs produce less contrast between /s/ and /ʃ/ than their chronological-age peers has two implications. First, reduced contrast may explain in part why the speech of children with CIs is less intelligible than that of their NH peers. Further research is needed to determine whether listeners respond negatively to the reduced contrast that children with CIs produce between /s/ and /ʃ/ and also whether children with CIs produce reduced contrast between phonemes other than /s/ and /ʃ/. Second, this finding supports the hypothesis

that production of contrast is related to auditory discrimination ability (Perkell, Matthies 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 NH peers.

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Endnotes

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 Milder and Liker, (2008) and Liker, Mildner, and Sindija (2007) there is no mention of exclusion of any tokens from the acoustic analysis.

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Table I. Characteristics of the children with cochlear implants

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

^c child included in the chronological age comparison

^d child included in the hearing age comparison

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 1 st implant	Age at 2 nd 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

Table III. Target words

	A	I	U
/s/	soccer	seashore	super
	sauce	sister	soup
	sun	seal	suitcase
/ʃ/	shark	sheep	chute
	shop	shield	shoe
	shovel	ship	sugar

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		NH	
	Number of tokens	Number of children (n=21)	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	

Table V. 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 hearing age comparison group and the number of children who produced those errors.

	CI		NH	
	Number of tokens	Number of children (n=32)	Number of tokens	Number of children (n=32)
Errors for /s/				
[f]	34	18	1	1
[θ]	15	9	18	12
[ʃ]	6	5	17	14
[ts]	8	5	15	13
stops	16	11	1	1
distortions	16	7	11	7
other	14	8	18	12
Total	109		81	
Errors for /ʃ/				
[s]	7	5	11	5
[tʃ]	25	15	22	14
distortions	6	2	2	1
other	12	7	8	7
Total	50		43	

Figure Captions

Figure 1. Mean peak ERB of productions of /s/ and /ʃ/ by the children with cochlear implants (CI) and the normally hearing children (NH) in the chronological age comparison group.

Figure 2. Mean peak ERB of productions of /s/ and /ʃ/ by the children with cochlear implants (CI) and the normally hearing children (NH) in the hearing age comparison group.