ACOUSTIC CHARACTERISTICS OF /s/ AND /ʃ/ IN CHILDREN WITH COCHLEAR IMPLANTS

by

Ann E. Todd

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Most children develop speech and language at a rapid rate; for example, typically developing children prodcouce approximately 100 words at 18 months of age and approximately 4,000 words by 6 years of age (e.g., Paul, 2007). A large body of research has shown that children with hearing loss have substantial and significant delays in speech and language development. For example, Moeller et al. (2007a, 2007b) followed a group of infants with mild to profound hearing loss and a group with normal hearing from 10 months of age to 24 months of age. Moeller et al. (2007a) found that on average the children with hearing loss produced simpler syllables and fewer consonants than the children with normal hearing. With the same group of children, Moeller et al. (2007b) found that the children with hearing loss were less understandable and produced words that were less complex than the normal hearing children at age 24 months. Difficulty with speech production is evident in older children with hearing loss as well. In a study by Blamey et al. (2001) school-age children with moderate to profound hearing loss had a larger variation in the degree to which their speech could be understood compared to normal hearing children. Wake, Hughes, Poulakis, Collins, and Rickards (2004) found that 7- and 8-year old children with mild to profound hearing loss performed more poorly on an articulation test than children with normal hearing.

Children with hearing impairment also have significant difficulty with language acquisition relative to typically hearing children. For example, Mayne, Yoshinaga-Itano, and Sedey, (1998) studied the receptive vocabularies of a group of children 8- to 22-months old with mild to profound hearing loss. Mayne and colleagues found that the children with hearing loss had smaller receptive vocabularies than normal hearing children. Mayne, Yoshinaga-Itano, Sedey, and Carey (1998) found that children 24- to 37-months old with mild to profound hearing loss had smaller expressive vocabularies than children with normal hearing. These lexical problems are also observed in older children with hearing loss. Wake, Hughes, Poulakis, Collins, and Rickards (2004) found that 7- and 8-year old children with mild to profound hearing loss did poorer on a receptive vocabulary test than normal hearing children. Blamey et al. (2001) followed a group of school-age children with mild to profound hearing loss. In this study the children with hearing loss showed a slower rate of receptive vocabulary growth compared to normal hearing children. In a study by Stelmachowicz, Pittman, Hoover, and Lewis (2004) 6- to 9-year old children with mild to severe hearing loss had more difficulty learning words than normal hearing children. Gilbertson and Kamhi (1995) studied word-learning in 7- to 10-year old children with mild to moderate hearing loss. In this study half of the children with hearing impairment had more difficulty learning new words and did more poorly on nonword repetition tasks than children with normal hearing. When looking at language in general Wake et al. (2004) found that children with hearing loss performed more poorly than children with normal hearing on a language test, and Blamey et al. (2001) found that children with hearing loss had scores on a language test that increased more slowly with age than normal hearing children.

Children who have severe to profound bilateral hearing loss “who receive little or no benefit from hearing aids” are candidates to receive a cochlear implant (Bradham & Jones, 2008, p. 1024). Cochlear implants are devices that provide electrical stimulation to the auditory nerve by means of an electrode array inserted into the cochlea. The Food and

Drug Administration approved the first type of cochlear implant in 1984 for adults and in 1986 for children, but it was not until 2000 that the FDA approved cochlear implantation for children as young as 12 months of age (Arts, Garber, & Zwolan, 2002). Currently there are over 120,000 people worldwide who use at least one cochlear implant (Wilson & Dorman, 2008). Children with profound hearing loss who become implanted with a cochlear implant have substantially better speech and language skills than children with profound hearing loss who use only hearing aids. Law and So (2006) studied the speech of 5- and 6-year old Cantonese-speaking children, half of whom used cochlear implants and half of whom used hearing aids. The children with cochlear implants had been implanted between 2 and 4 years of age. Law and So found that the children with cochlear implants correctly produced a higher percentage of consonants than did the children with hearing aids. Tomblin et al. (1999) compared the expressive syntax and receptive language of children with cochlear implants and children with hearing aids. This study found that the children with cochlear implants had significantly better scores on a syntax test than the hearing aid users who were profoundly deaf. Furthermore, Tomblin et al. found that performance on the syntax test was correlated with years of cochlear implant experience and not chronological age for the cochlear implant group, but for the hearing aid group syntax performance was strongly correlated with chronological age. This suggests that the higher performance of the cochlear implant users was due to their cochlear implant experience. The cochlear implant users as a group also performed significantly better on the receptive language test than hearing aid users of a variety of different hearing losses.

Although children with cochlear implants outperform children with hearing aids, they do not perform as well as normal hearing children in speech and language. Several studies have found that the extent to which the speech of children with cochlear implants is understood is lower than that of normal hearing children. For example, Chin, Tsai, and Gao (2003) studied the speech of children with cochlear implants who were 2 to 10 years of age who had received a cochlear implant before the age of six. This study found that children with cochlear implants were less well understood than children with normal hearing when comparing the groups by chronological age and by hearing age (the amount of time using a cochlear implant for the cochlear implant users). Peng, Spencer, and Tomblin (2004) studied the speech of adolescents with cochlear implants who were 9 to 18 years of age. The age of cochlear implantation in this group ranged from 2 to 11 years. At the time of the study each of the cochlear implant users had had their device for 7 years. The percent of speech produced by the cochlear implant users which was understandable was approximately 71% which is below that of normal hearing individuals whose speech is nearly 100% intelligible by around 4 years of age (Chin et al., 2003). Some studies have examined the specific speech sounds that children with cochlear implants have difficulty acquiring. Blamey, Barry, and Jacq (2001) studied the speech sounds present in the speech production of children with cochlear implants who had been implanted between 2 and 5 years of age. These researchers found that by 6 years after cochlear implantation the speech sounds /ɔɪ, ʒ, t, s, z, tʃ, θ/ were not produced correctly 50% of the time in the speech of most of the children. Tomblin, Peng, Spencer, and Lu (2008) looked at the number of speech sounds that were correctly produced out of the total number of speech sounds in words that were understood in the speech samples of cochlear implant users who had been implanted between 2 and 7 years of age. Tomblin and colleagues found that after 6 years of cochlear implant use, the cochlear implant users produced on average 76% of speech sounds correctly and after 10 years produced 81% of speech sounds correctly.

Other studies have looked at the phonological processing of children with cochlear implants by examining these children's ability to repeat nonwords. Nonword repetition tasks are a reflection of children's ability to process, remember, and reproduce phonological patterns of varying lengths and levels of familiarity (Dillon & Pisoni, 2006). Roy and Chiat (2004) found that 2- and 3-year old typically hearing children correctly produced on average three out of six nonwords that were three syllables in length and had phonological patterns found in English. Research suggests children with cochlear implants have more difficulty with this task than typically hearing children. Cleary, Dillon, and Pisoni (2002) studied nonword repetition in 8- and 9-year-old children with cochlear implants who had been deaf for 1;6 to 5;3 years before being implanted. The children accurately imitated, on average, 39% of the initial consonants of nonwords which were two to five syllables in length, but showed wide variability in performance. When just considering the initial consonants of the nonwords (/p, b, t, d, k, g, f, v, s/), Cleary et al. found that the children were most accurate on the sounds made in the alveolar position i.e., /t, d, s/ and second most accurate on other stops /p, b, k, g/.

In a study of phonological awareness by James, Rajput, Brinton, and Goswami (2007) 7- to 10-year-old children who had been implanted between 2 and 3.6 years performed similarly to reading-level-matched typically hearing children on tasks of syllable and rhyme awareness, but performed significantly worse than the reading-level-matched typically hearing children on phoneme awareness when unable to use orthography as cues. When comparing the children with cochlear implants to age-matched typically hearing children, James et al. found that the children with cochlear implants performed similarly to the typically hearing children on tasks of syllable awareness, but performed significantly worse on rhyme and phoneme awareness. Schorr, Roth, and Fox (2008) examined the phonological processing of 5- to 14-year-old children with cochlear implants relative to age-matched typically hearing children. This study found that the children with cochlear implants performed significantly worse on average than the typically hearing children in tasks of phonological awareness, phonological memory, and phonological retrieval speed.

When examining the speech of children with cochlear implants most studies have used transcription as a way to describe these children's speech (e.g., Blamey, Barry, & Jacq, 2001; Cleary, Dillon, Pisoni, 2002; Dillon & Pisoni, 2006; Schorr, Roth, Fox, 2008; Tomblin, Peng, Spencer, & Lu, 2008). Transcription is an accuracy measure that requires coding children's speech sounds into discrete categories; however, children do not always produce sounds that fall into distinct categories. There is evidence that children sometimes produce speech sounds that fall between two categories. For example Schellinger (2008) took typically developing children's productions of /s/ and /θ/ that were obtained from a word repetition task, and placed the productions into the following categories: correct /s/, [s] for /θ/ substitutions, productions intermediate between /s/ and

/θ/, [θ] for /s/ substitutions, or correct /θ/. Schellinger then had adults listen to the children's productions which were preceded by either of two types of carrier phrases, and judge the productions as either correct /s/ or incorrect /s/. Schellinger found that the average percent of correct-/s/ judgments that each category of stimulus received was significantly different from all others and that listeners' judgments on average matched the researchers' transcriptions e.g., productions that the researchers transcribed as between /s/ and /θ/ were judged on average as correct-/s/ approximately half of the time. This suggests that for the productions that were transcribed as between /s/ and /θ/ the listeners as a group also heard something between /s/ and /θ/. Furthermore, when looking only at the responses that showed an intra-listener inconsistency across carrier phrase Schellinger found that on average this inconsistency occurred significantly more often when the stimulus item was transcribed as intermediate between /s/ and /θ/.

Acoustic analysis is a way to describe individuals' productions of speech sounds in a way that is more gradient than transcription. For example, studies that examine the acoustic correlates for sibilant fricatives have used spectral moments analysis to describe the energy distribution in the spectra of speech sounds (e.g., Baum & McNutt, 1990, Li, Edwards, & Beckman, 2009, Uchanski & Geers, 2003). Spectral moments analysis include the first, second, third, and fourth spectral moments which correspond to centroid (mean), standard deviation, skewness, and kurtosis of a spectrum. In spectral moments analysis the frequencies present in a spectrum are multiplied by the intensity level at which they were produced (Li, Edwards, Beckman, 2009).

In English, differences in spectral moments have been used to describe fricative production in both adults and children. For example, Baum and McNutt (1990) analyzed the acoustic signal of /s/ and /θ/ in 5- to 8-year old Canadian-English-speaking children who produced /s/ in a way that sounded like /θ/, to investigate if these children had an actual [θ] for /s/ substitution or if their productions of /s/ differed from their productions of /θ/. This study found that the children's average centroid values for /s/ were significantly higher than centroid values for /θ/. The results of this study suggest that while it sounded as though the children were producing [θ] for /s/, their productions of /s/ differed acoustically from their productions of /θ/. Li et al. (2009) found that differences in centroid values could be used to classify 100% of /s/ and /ʃ/ productions in the speech of adult American-English speakers. Differences in centroid values could also classify most of the correct productions of /s/ and /ʃ/ by 2- to 5-year-old English-speaking children.

The fricatives /s/ and /ʃ/ are later-acquired sounds in children with typical hearing (Smit, Hand, Freilinger, Bernthal, Bird, 1990). Children with cochlear implants may be even more challenged in the acquisition of /s/ and /ʃ/, since the frequency resolution provided by cochlear implants is poorer than that provided by normal hearing. Summerfield et al. (2002) examined the performance of children with cochlear implants in distinguishing /s/ and /ʃ/. The subjects tested included children 4 to 10 years of age who had been implanted between 2 and 7 years of age and had used their cochlear implants from 1 to 6 years; and normal hearing children between 2.5 and 5.5 years of age.

Summerfield et al. found that all of the normal hearing children scored above chance in differentiating the words “sea”, “she”, “Sue”, and “shoe”, but only 14 out of 27 children with cochlear implants scored above chance. It was found that the children who had more experience with their cochlear implants performed significantly better on this task than children who had less experience. The researchers also created synthetic fricatives that sounded between /s/ and /ʃ/ and attached vowels that contained information indicating either /s/ or /ʃ/. While the vowel had a significant effect on the decisions of all of the children with normal hearing, the vowel had a significant effect on the decisions of only 4 of 13 children with cochlear implants. A weak positive correlation was found between the two tasks for the children with cochlear implants, suggesting that to some extent the children with implants who considered the /s/ and /ʃ/ cues within the vowel, were better able to distinguish /s/ and /ʃ/.

Studies on the acoustic characteristics of speech of children with cochlear implants have shown these children do not produce the fricatives /s/ and /ʃ/ like typically hearing children. Uchanski and Geers (2003) compared the acoustic characteristics of speech of 181 8- and 9-year old children with cochlear implants to typically hearing 8- and 9-year old children. The children in this study had been implanted at least four years prior to the study. To elicit words with target sounds from the children with cochlear implants, the researchers spoke or signed and spoke a sentence, then presented the sentence in writing, and then had the children produce the sentence. Acoustic analysis was done only on productions that maintained the fricative feature. When examining the first (centroid), third (skewness), and fourth (kurtosis) spectral moments, Uchanski and Geers found that the /s/ productions of typically hearing children showed higher centroid values, more negative skewness, and greater kurtosis than the /ʃ/ productions, which Uchanski and Geers claimed was consistent with the findings of other studies. Some of the children with cochlear implants did not show this pattern between the spectra of /s/ and /ʃ/. Twenty-nine percent of the children with cochlear implants produced average centroid values that were lower for /s/ than for /ʃ/. Furthermore, 19% produced differences between average skewness of /s/ and /ʃ/ that were out of the range of the values of the typically hearing children, and 38% produced differences between average kurtosis of /s/ and /ʃ/ that was out of the range of the values of the typically hearing children. When examining accuracy in manner of production, Uchanski and Geers found that the children with cochlear implants only produced 49 percent of target /s/ and /ʃ/ as fricatives.

In a longitudinal study, Mildner and Liker (2008) examined acoustic characteristics of the speech of 10 Croatian children with cochlear implants and made comparisons to typically hearing, age- and sex-matched children. Testing took place at four points in time over the course of 46 months, the first testing time being near the time of implantation. Subjects had been implanted between 3 and 10 years of age, the median age of implantation being 7 years 6 months. The experimenters recorded the subjects naming pictures and numbers. The centroid values for /s/ and /ʃ/ averaged across the typically hearing children were significantly different. The children with cochlear implants did not show a statistically significant difference between average centroid values for /s/ and /ʃ/ until the fourth testing point, yet even at the fourth testing the centroid values of /s/ and /ʃ/ of the children with cochlear implants were not as well separated as that of the typically hearing children. Standard deviations of the centroid values of /s/ and /ʃ/ produced by the children with cochlear implants were much larger than that of the typically hearing children at the second and third testing time, but were similar to that of the typically hearing children at the fourth testing time.

The previously mentioned studies which analyzed the acoustic characteristics of /s/ and /ʃ/ produced by children with cochlear implants, matched subjects on chronological age and sex. However, it would also be valuable to match subjects on hearing-age i.e., age since receiving the first cochlear implant. Although children who use cochlear implants used hearing aids before being implanted, these children received "little or no benefit from hearing aids" (Bradham & Jones, 2008, p. 1024; Flipsen & Colvard, 2005). Most children with cochlear implants are not implanted before 12 months of age and therefore begin receiving speech input later than typically hearing children which contributes to the delay in speech production seen in children with cochlear implants. A small scale study by Wright, Purcell, and Reed (2002) showed that children who received a cochlear implant at 12 to 15 months of age showed a delay in vocalizations and babbling relative to typically hearing children. Therefore, hearing age is one way to quantify the expected performance of children with hearing loss in speech and language. One study that looked at the hearing ages of children with cochlear implants found that the phonological processes seen in 2 out of 5 of the children with cochlear implants indicated a phonological delay when considering chronological ages, but not when considering hearing ages (Buhler, De Thomasis, Chute, & DeCora, 2007).

The purpose of the present study was to analyze the productions of /s/ and /ʃ/ in children with cochlear implants in relation to two comparison groups of typical hearing children, one matched on hearing age, and the other matched on chronological age. The hypotheses of the present study were that the children with cochlear implants as a group would show less contrast between /s/ and /ʃ/ and more variability in their productions of /s/ and /ʃ/ than children with typical hearing.

To date, most research on the speech of children with cochlear implants has examined the speech of children with one cochlear implant. In the current study, the children with cochlear implants were implanted in both ears (bilaterally). Having two ears in typically hearing people aids in sound localization along the azimuth and speech perception in noise. Bilateral cochlear implants have been found to aid some individuals in sound localization and speech perception under certain conditions (e.g., Litovsky et al. 2004; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006). However, it is currently unknown whether bilateral implantation has a benefit on speech production over unilateral implantation. It could be that two cochlear implants provide users with better speech perception and therefore bilateral cochlear implant users may have better speech production than unilateral cochlear implant users. The current study was not designed to investigate this question directly because a unilateral control group was not included. However, the performance of children with bilateral cochlear implants is of interest, given the literature on the difficulties that children with cochlear implants have with sibilant fricatives (/s/ and /ʃ/).

Methods

Participants

Participants included 18 children with bilateral cochlear implants who ranged from 4- to 9-years of age. Twelve of the children were females and 6 were males. Participants were recruited from a larger study on hearing in children with bilateral cochlear implants, from various cochlear implant centers around the United States. All of the children spoke English as a first language except one child who used American Sign Language at home. The children with cochlear implants (CI's) had no other diagnoses besides hearing loss. Children who had hearing loss due to auditory neuropathy were excluded from the study. One participant was excluded from the study due to suspicions of a developmental disorder. The average age of implantation of the first cochlear implant was 1;6 (years;months). Age of implantation of the first cochlear implant ranged from 0;9 to 5;1. Twenty-six 2- to 5-year old children with typical hearing and development acted as the comparison groups. There were 19 females and 7 males. The typically hearing children were recruited for a larger study on phonological development from schools and day care centers in Columbus, Ohio**.** All of the typically hearing children spoke English as a first language and passed a hearing screening. Each child with typical hearing was matched to a child with CI's on hearing-age, gender, and Peabody Picture Vocabulary Test 4 (PPVT-4) standard score, or was matched to a child with CI's on chronological age, gender, and PPVT-4 standard score. Most of the children were white. Table 1 provides demographic data for the children with CI's and the two comparison groups. The hearing-age comparison group refers to the typically hearing children who were matched to the children with CI's on hearing age. The chronological age comparison group refers to the typically hearing children who were matched to the children with CI's on chronological age.

Insert Table 1

Stimuli

The stimuli used in the repetition task included 9 familiar real words with /s/ in initial position and 9 words with /ʃ/ in initial position (see Table 2). Following /s/ and /ʃ/ was one of the three vowels /ɑ, i, u/ which were distributed evenly throughout the stimuli. Vowels producing similar coarticulatory effects were grouped together. That is, /ɑ/, /ʌ/, /ɔ/ were grouped together in the /ɑ/ category; /i/ and /ɪ/ were grouped together in the /i/ category; and /u/ and /ʊ/ were grouped together in the /u/ category.

The auditory stimuli of the repetition task were digital recordings of words spoken by an adult female in a child-directed speech register. Recordings were made at a 22,500

Hz sampling rate. Visual stimuli of the repetition task were photographs that corresponded to the auditory stimuli e.g., for the stimulus word "sister" there was a photograph of two girls. The order of the stimuli was randomized.

Insert Table 2

Procedure

The children with CI's were tested in a sound-attenuated room and the children with typical hearing were recorded in a quiet room at their school or day care center. The children were seated at a table on which there was a laptop and computer speakers. The children were told that they would see pictures on the computer screen and hear words from the computer, and that it was their job to repeat the words they heard. The children were provided with a practice task before the testing stimuli was presented. Each auditory stimulus with its picture was played once unless the child said the wrong word or the child's production was difficult to hear. Each time a new stimulus was presented a figure of an animal on the side of the computer screen climbed farther up a ladder to indicate to the child how much further until the end of the task. All of the children's productions were digitally recorded. The typically hearing children were recorded in the quietest room in their school. Two standardized tests were also administered: the *Peabody Picture Vocabulary Test 4* (Dunn & Dunn, 2007) to measure receptive vocabulary and the *Goldman Fristoe Test of Articulation 2* (Goldman & Fristoe, 2000) to measure articulatory ability. The testing for the children with cochlear implants was completed within a two-day period, while the testing for the children with typical development was completed within a oneweek period.

Transcription

A fairly narrow transcription was made by a trained native speakers/phonetician using a combination of the auditory signal, the spectrogram, and the waveform. Each initial fricative and vowel produced by the children was transcribed unless a production could not be heard. Productions were transcribed as correct or incorrect, the type of error was coded (distortion, substitution, deletion), and the substituted sound was written in the case of substitution errors.

Interrater Agreement for Transcription

Inter-rater reliability was calculated separately for the children with normal hearing and the children with CI's. For the children with normal hearing, a second transcriber independently transcribed the productions of 10 children (out of the database of the productions of 80 children) for a broad range of consonants. Phoeneme-by-phoneme inter-rater agreement was 89% for accuracy (correct or incorrect) and 92% for the sound the transcriber heard produced. For the children with CI's, a second transcriber independently transcribed /s/ and /ʃ/ for three children (aged 4;1, 6;2, and 7;1). Phoneme-by-phoneme inter-rater agreement was 94.5% both on accuracy and on the sound the transcriber heard produced.

Acoustic Analysis

Transcription and acoustic analysis were conducted using the Praat software (Boersma & Weenink, 2006). Correct productions were analyzed acoustically. The onset of frication was marked where there was an increase in energy in both the waveform and the spectrogram. The end of the fricative was marked at the first glottal pulse of voicing. The criteria used for marking the onset and offset of frication were chosen, because the locations specified could be reliably identified. See Figure 1 for an example of these measurement points. The first spectral moment i.e., centroid, was calculated from the middle forty milliseconds of the fricative. A two-way repeated-measures ANOVA with group (children with CI's and children with normal hearing) as the between-subjects factor and fricative (/s/ and /ʃ/) as the within-subjects factor was calculated on the group comprised of the children with CI's and the hearing-age (HA) comparison group, and on the group comprised of children with CI's and the chronological-age (CA) comparison group.

Insert Figure 1

Error Analysis

Percent correct /s/ and percent correct /ʃ/ were calculated for each of the groups of children. In order to describe the substitutions for /s/ and /ʃ/ produced by each group of children, the most frequent sound substitutions were listed and the percent of total errors that each sound made up was calculated.

Results

Acoustic Analysis

Children with CI's and HA comparison group

Figure 2 shows median centroids and inter-quartile ranges for both /s/ and /ʃ/ for the children with CI's and the hearing-age comparison group. A two-way ANOVA showed a significant main effect of group ($F[1,32] = 8.62$, $p = .006$). It can be observed in Fig. 2 that the centroid values of the children with CI's are lower than those of their typical hearing peers. There was also a significant main effect of fricative ($F[1,32] = 164$, $p < .001$). As can be seen in Fig. 2, the centroid value for /s/ is higher than the centroid value for /ʃ/, as expected. There was also a significant group by fricative interaction ($F[1,32] = 5.09$, $p = .03$). As Fig. 2 shows, there is a greater difference in centroid values between the two groups for /s/, as compared to /ʃ/. Figure 2 also shows that there is a greater range of centroid values for the productions of children with typical hearing, as compared to those of the children with CI's.

Insert Figure 2

Children with CI's and CA comparison group

A similar pattern of results was observed for the comparison of children with CI's to their chronological-age peers with typical hearing. Figure 3 shows median centroids and inter-quartile ranges for both /s/ and /ʃ/ for the children with CI's and the chronological age comparison group. A two-way ANOVA again showed a significant main effect of fricative ($F[1,19] = 121$, $p <. 001$), with centroid values for /s/ higher than those for /ʃ/. A significant main effect of group was not found; however, the difference approached significance ($F[1,19] = 4.134$, $p = .056$) . There was also a significant group by fricative interaction ($F[1,19] = 5.69$, $p = .028$). Again, there is a greater group difference in centroid values for /s/, as compared to /ʃ/. Figure 3 again shows a greater range of centroid values for the productions of children with typical hearing, as compared to those of the children with CI's.

Insert Figure 3

Individual children

Figures 4 through 8 show graphs of individual children's productions of /s/ and /ʃ/. The productions of five children with cochlear implants are represented to illustrate the range of performance among the children with CI's. Each figure shows the productions of a child with CI's in comparison to his/her hearing-age and chronological-age matches' productions or just to his/her hearing-age match's productions. While differences were found between the group of children with CI's and the group of children with typical hearing, some of the children with CI's produced /s/ and /ʃ/ with centroid values similar to those of the typically hearing children. In Figs. 4 and 5, one can see that the centroids of /s/ produced by children with CI's are high in frequency and have variability similar to that of the typically hearing children. Figs. 6 through 8 show productions of /s/ by children with CI's, which are different from those of the typically hearing matches. The /s/ productions of these children with CI's have low frequency centroid values, and in two of the three children with CI's (seen in Figs. 7 and 8) the centroid values of /s/ show less variability than those of the typically hearing children.

Another observation that can be made from Figs. 4 through 8 is that the variability in centroid values is not systematically related to the identity of the following vowel, for either the children with CI's or the children with typical hearing. This is not surprising, given that the centroid values were measured at the midpoint of /s/ and /ʃ/.

Insert Figure 4

Insert Figure 5

Insert Figure 6

Insert Figure 7

Insert Figure 8

Error Analysis

The percent of total productions of /s/ and /ʃ/ that were produced correctly is shown in table 3 for each group of children. As can be seen in table 3, when considering accuracy the children with cochlear implants performed more similarly to the children in the hearing-age comparison group than to the children in the chronological-age comparison group.

Insert Table 3

Errors for /s/

For each group, the majority of substitutions produced for /s/ were of the fricative type. Table 4 shows specific substitutions for /s/. [f] made up the highest percentage of total errors among the children with cochlear implants. [ʃ] made up the highest percentage of total errors among the HA comparison group, and [θ] made up the highest percentage of total errors among the CA comparison group.

Insert Table 4

Errors for /ʃ/

For each group except the CA comparison group, the majority of substitutions for /ʃ/ were of the affricate type. [tʃ] made up the highest percentage of total errors among the children with CI's and the HA comparison group. [s] made up the highest percentage of total errors for /ʃ/ among the CA comparison group.

Insert Table 5

Discussion

The results of the acoustic analysis showed a significant difference between group centroid values of /s/ and /ʃ/. This result is consistent with other studies that found that the measure of centroid is able to distinguish between /s/ and /ʃ/ in children's productions (e.g., Li, Edwards, Beckman, 2009).

A significant group difference was found between the group of children with CI's and the hearing-age comparison group, and the difference between the group of children with CI's and the chronological-age comparison group approached significance. It may be that children with CI's in general produce /s/ and /ʃ/ with centroids that are lower in frequency than children with typical hearing. One factor that must be taken into account when interpreting this result is that the children in the hearing age comparison group were, by definition, younger than the children with CI's. Younger children have smaller vocal tracts and therefore may produce /s/ and /ʃ/ at higher frequencies. This may be why the comparison between children with CI's and their chronological age peers with typical hearing was only marginally significant. However, comparisons of individual subjects (as shown in Figs. 4 through 8) showed that some children with CI's produced /s/ with centroid values lower than their chronological age peers with typical hearing, and the smaller sample size of 11 for the chronological age comparison group (relative to the sample size of 18 for the hearing age comparison group) also contributed to finding only a marginally significant difference between groups.

Less variability in centroid values was also observed in the productions of the children with CI's relative to those of the children with normal hearing. Future research could investigate if reduced variability in spectral measures of /s/ and /ʃ/ productions of children with CI's is seen when examining the offset of /s/ and /ʃ/. The offset of /s/ and /ʃ/ is adjacent to the vowel and therefore would most likely vary with the vowel. Findings that children with cochlear implants produce less robust cues for the following vowel in their productions of /s/ and /ʃ/ than typically hearing children would be in line with the speech perception findings reported by Summerfield et al. (2002) in which most of the children with cochlear implants did not attend to cues for /s/ and /ʃ/ contained in the vowel.

A significant group by fricative interaction was found which is consistent with findings from other studies (Uchanski & Geers, 2003; Mildner & Liker, 2008). This suggests that children with CI's are not producing as much of a distinction between /s/ and /ʃ/ (even for productions that were transcribed as correct) as typically hearing children. The group by fricative interaction was seen when comparing the children with CI's to the chronological-age comparison group and when comparing the children to the hearing-age comparison group. This suggests that the supposed reduced contrast between /s/ and /ʃ/ of the children with CI's compared to chronological-age peers is not solely due to the children with CI's having a shorter hearing age. Furthermore, the fact that children with CI's perform more similarly to their typical hearing peers for /ʃ/ and more differently from their peers for /s/ suggests a perceptual explanation for this difference. The concentration of energy characteristic of /s/ is above 4000 Hz, while the concentration of energy characteristic of /ʃ/ is below 4000 Hz. For virtually all CI users, the filters in CI's assigned to frequencies above 4000 are very wide, so there is poor frequency resolution for /s/.

The accuracy analysis showed that /ʃ/ was produced more accurately than /s/ by all groups of children. As expected, the chronological-age comparison group produced the highest percent correct /s/ and /ʃ/. The accuracy of the children with cochlear implants was more similar to that of the hearing-age comparison group; however, the errors produced by the two groups were different. The errors produced by the children with cochlear implants most likely in part reflect a perceptual difficulty during the word-repetition task, whereas, the errors produced by the children with typical hearing largely reflect a difficulty with speech production. The most frequent substitution for /s/ produced by the hearing-age comparison group was [ʃ] and by the chronological-age comparison group was [θ]. [θ] productions for /s/ (or fronting of /s/) is a common /s/ substitution (Peña-Brooks & Hedge, 2000), and /ʃ/ is a sibilant (high energy) fricative like /s/ so it is therefore not surprising that these sounds were substituted for /s/. The most frequent substitution in the children with CI's was [f]. It is likely that the children with CI's had difficulty perceiving /s/ during the word repetition task and mistook /s/ for /f/. The most frequent substitution for /ʃ/ was [tʃ] among the children with CI's and the hearing-age comparison group. The most frequent substitution for /ʃ/ among the chronological-age comparison group was [s]. It may be that the children with CI's made errors for /ʃ/ that were more similar to the hearing-age comparison group than to the chronological-age comparison group, because the children with CI's had similar lengths of perceptual experience with speech sounds as the hearing-age comparison group. Since /ʃ/ is produced with energy at lower frequencies than /s/, it is expected that children with CI's would have an easier time perceiving /ʃ/ than /s/.

The fact that a word repetition task was used instead of a picture naming task is one limitation of this study. Since a word repetition task was used, it is difficult to know what speech sound errors were due to perceptual difficulties of the children with CI's and which were due to difficulties with productions. The current study only did acoustic analysis on correct productions of /s/ and /ʃ/, so to preclude analysis on substitutions for /s/ and /ʃ/ that were due to perceptual errors. A picture naming task would most likely elicit more productions that could be analyzed acoustically than a word repetition task.

Further research needs to be done to determine what characteristics separate children with CI's who produce /s/ and /ʃ/ with centroids similar to typically hearing children from those that produced /s/ and /ʃ/ with centroids that show differences from typically hearing children. Characteristics that could be examined in children with cochlear implants in relation to the acoustic characteristics of /s/ and /ʃ/ include age, hearing-age, speech perception performance, and characteristics of individuals' cochlear implants.

In spite of the limitations of the current study, there are important findings. A significant group by fricative interaction was found. Production of /s/ by the children with CI's appeared to be particularly different from the productions of /s/ by children with typical hearing, showing low frequency centroids with limited variability. These differences were evident even when comparing the children with CI's to a hearing-age comparison group, suggesting that production of /s/ in children with cochlear implants is affected by the poor frequency resolution provided by cochlear implants above 4000 Hz.

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References

Arts, H. A., Garber, A., Zwolan, T. A. (2002). Cochlear implants in young children. *Otolaryngologic Clinics of North America, 35*, 925-943.

Baum, S. R., & McNutt, J. C. (1990). An acoustic analysis of frontal misarticulation of /s/ in children. *Journal of Phonetics, 18*, 51-63.

Blamey, P., Barry, J. G., & Jacq, P. (2001). Phonetic inventory development in young cochlear implant users 6 years postoperation. *Journal of Speech, Language, and Hearing Research, 44*, 73-79.

Blamey, P. J., Sarant, J. Z., Paatsch, L. E., Barry, J. G., Bow, C. P., Wales, R. J., et al. (2001). Relationship among speech perception, production, language, hearing loss, and age in children with impaired hearing. *Journal of Speech, Language, and Hearing Research, 44*, 264-285.

Bradham, T., & Jones, J. (2008). Cochlear implant candidacy in the United States: Prevalence in children 12 months to 6 years of age. *International Journal of Pediatric Otorhinolaryngology, 72*, 1023-1028.

Buhler, H.C., De Thomasis, B., Chute. P., & DeCora, A. (2007). An analysis of phonological process use in young children with cochlear implants. *Volta Review, 107(1)*, 55-74.

Chin, S. B., Tsai, P. L., & Gao, S. (2003). Connected speech intelligibility of children with cochlear implants and children with normal hearing. *American Journal of Speech-Language Pathology, 12*, 440-451.

Cleary, M., Dillon, C., & Pisoni, D. B. (2002). Imitation of nonwords by deaf children after cochlear implantation: preliminary findings. *The Annals of Otology, Rhinology & Laryngology, 111*(Suppl. 189), 91-96.

Dillon, C. M., & Pisoni, D. B. (2006). Nonword repetition and reading skills in children who are deaf and have cochlear implants. The Volta Review, 106(2), 121-145.

Dunn, L. M., & Dunn, D. M. (2007). *Peabody Picture Vocabulary Test (4th ed.).* (n.p.): Wascana Limited Partnership.

Flipsen, P., Jr., & Colvard, L. G. (2006). Intelligibility of conversational speech produced by children with cochlear implants. *Journal of Communication Disorders, 39*, 93-108.

Gilbertson, M., & Kamhi, A. G. (1995). Novel word learning in children with hearing impairment. *Journal of Speech and Hearing Research, 38*(3), 630-642.

Goffman, L. (1999). Prosodic influences on speech production in children with specific language language impairment and speech deficits: Kinematic, Acoustic, and Transcription Evidence. *Journal of Speech, Language, and Hearing Research, 42*, 1499-1517.

Goffman, L. (2004). Kinematic differentiation of prosodic categories in normal and disordered language development. *Journal of Speech, Language, and Hearing Research, 47*, 1088-1102.

Goldman, R. & Fristoe, M. (2000). *Goldman Fristoe Test of Articulation.* Circle Pines, MN: American Guidance Service, Inc.

James, D., Rajput, K., Brinton, J., & Goswami, U. (2007). Phonological awareness, vocabulary, and word reading in children who use cochlear implants: Does age of implantation explain individual variability in performance outcomes and growth? *Journal of Deaf Studies and Deaf Education, 13*(1), 117-137.

Law, Z. W. Y., & So, L. K. H. (2006). Phonological abilities of hearing-impaired Cantonese-speaking children with cochlear implants or hearing aids. *Journal of Speech, Language, and Hearing Research, 49*, 1342-1353.

Li, F., Edwards, J., & Beckman, M. E. (2009). Contrast and covert contrast: The phonetic development of voiceless sibilant fricatives in English and Japanese toddlers. *Journal of Phonetics 37*(1), 111-124.

Litovsky, R., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P., & Yu, G. (2004). Bilateral cochlear implants in adults and children. *Archives of Otolaryngology-Head and Neck Surgery, 130*, 648-655.

Litovsky, R., Parkinson, A., Arcaroli, J., & Sammeth, C. (2006). Simultaneous bilateral cochlear implantation in adults: A multicenter clinical study. *Ear & Hearing*, 26(4), 714-731.

Mayne, A. M., Yoshinaga-Itano, C., & Sedey, A. L. (1998). Receptive vocabulary development of infants and toddlers who are deaf or hard of hearing. *Volta Review, 100*(5), 29-52.

Mayne, A. M., Yoshinaga-Itano, C., Sedey, A. L., & Carey, A. (1998). Expressive vocabulary development of infants and toddlers who are deaf or hard of hearing. *Volta Review, 100*(5), 1-28.

Mildner, V., & Liker, M. (2008). Fricatives, affricates, and vowels in Croatian children with cochlear implants. *Clinical Linguistics & Phonetics, 22*(10-11), 845-856.

Moeller, M. P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., Peterson, B. et al. (2007a). Vocalizations of infants with hearing loss compared with infants with normal hearing: Part I – phonetic development. *Ear & Hearing, 28*(5), 628-642.

Moeller, M. P., Hoover, B., Putman, C., Arbataitis, K., Bohnenkamp, G., Peterson, B. et al. (2007b). Vocalizations of infants with hearing loss compared with infants with normal hearing: Part II – transition to words. *Ear & Hearing, 28*(6), 740-753.

Moeller, M. P., Tomblin, J. B., Yoshinaga-Itano, C., Connor, C. M., & Jerger, S. (2007). Current state of knowledge: Language and literacy of children with hearing impairment. *Ear & Hearing, 28*(6), 740-753.

Nicholas, J. G., & Geers, A. E. (2008). Expected test scores for preschoolers with a cochlear implant who use spoken language. *American Journal of Speech-Language Pathology, 17*, 121-138.

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

Paul, R., (2007). *Language disorders from infancy through adolescence: Assessment & intervention* (3rd ed.). St. Louis, Missouri: Mosby, Inc.

Peña-Brooks, A. & Hedge, M. N. (2000). *Assessment & treatment of articulation and phonological disorders in children*. Austin, TX: PRO-ED, Inc.

Peng, S., Spencer, L. J., & Tomblin, J. B. (2004). Speech intelligibility of pediatric cochlear implant recipients with 7 years of device experience. *Journal of Speech, Language, and Hearing Research, 47*, 1227-1236.

Roy, P., & Chiat, S. (2004). A prosodically controlled word and nonword repetition task for 2- and 4-year-olds: Evidence from typically developing children. *Journal of Speech, Language, and Hearing Research, 47*, 223-234.

Schellinger, S. K. (2008). The role of intermediate productions and listener expectations on the perception of children's speech. Master's thesis. Department of Communicative Disorders, University of Wisconsin-Madison.

Schorr, E. A., Roth, F. P., & Fox, N. A. (2008). A comparison of the speech and language skills of children with cochlear implants and children with normal hearing. *Communicative Disorders Quarterly*, 29(4), 195-210.

Smit, A. B., Hand, L., Freilinger, J. J., Bernthal, J. E., & Bird, A. (1990). The Iowa articulation norms project and its Nebraska replication. *Journal of Speech and Hearing Disorders, 55*, 779-798.

Stelmachowicz, P. G., Pittman, A. L., Hoover, B. M., & Lewis, D. E. (2004). Novel-Word learning in children with normal hearing and hearing loss. *Ear & Hearing, 25*(1), 47-56.

Summerfield, A. Q., Nakisa, M. J., McCormick, B., Archbold, S., Gibbin, K. P., O'Donoghue, G. M. (2002). Use of Vocalic Information in the Identification of /s/ and /ʃ/ by Children with Cochlear Implants. *Ear & Hearing, 23*(1), 58-77.

Tomblin, J. B., Peng, S., Spencer, L. J., & Lu, N. (2008). Long-Term trajectories of the development of speech sound production in pediatric cochlear implant recipients. *Journal of Speech, Language, and Hearing Research, 51*, 1353-1368.

Tomblin, J. B., Spencer, L., Flock, S., Tyler, R., & Gantz, B. (1999). A comparison of language achievement in children with cochlear implants and children using hearing aids. *Journal of Speech, Language, and Hearing Research, 42*, 497-511.

Uchanski, R. M., & Geers, A. W. (2003). Acoustic characteristics of the speech of young cochlear implant users: A comparison with normal-hearing age-mates. *Ear & Hearing, 24*(1S), 90S-105S.

Wake, M., Hughes, E. K., Poulakis, Z., Collins, C., & Rickards, F. W. (2004). Outcomes of children with mild-profound hearing loss at 7 to 8 years: A population study. *Ear & Hearing, 25*(1), 1-8.

Wilson, B. S., & Dorman, M. F. (2008). Cochlear implants: A remarkable past and a brilliant future. *Hearing Research, 242*, 3-21.

Wright, M., Purcell, A., & Reed, V. A. (2002). Cochlear implants and infants: Expectations and outcomes. *Annals of Otology, Rhinology, and Laryngology*, 111, 131-137.

Table1. Demographic characteristics of the children with CI's and the two comparison groups with typical hearing.

Groups	Mean Age (standard deviation in parentheses)	Mean Hearing Age (standard deviation in parentheses)	Mean PPVT raw score (standard deviation in parentheses)	Mean PPVT standard score (standard deviation in parentheses)	Males/Total
CI-1[a]	5;8 (1.34)	4;1 (1.01)	89.05 (24.43)	98.55 (13.84)	6/18
HA[b]	4;1 (0.99)	4;1 (0.99)	46.44 (10.48)	99.16 (10.82)	6/18
CI-2[c]	4;10 (0.69)	3;7 (.69)	80.90 (15.88)	102.63 (13.49)	1/11
CA[d]	4;9 (0.59)	4;9 (0.59)	59.90 (7.80)	106.45(11.26)	1/11

[a]The CI-1 group includes all 18 children with CI's. This group was compared to the HA group.
[b]The hearing-age comparison group.
[c]The children in the CI-2 group are a subset of children from the CI-1 group. These children with CI's were also compared to children of the same chronological age. Only 11 of the children with CI's are in the CI-2 group, because 7 of the children with CI's were older than 5;11 and therefore did not have an age match in the data base of typical hearing children.
[d]The chronological age comparison group. Three typically hearing children were both in the hearing-age comparison group and the chronological age comparison group.

Table 2. Stimuli used in the word repetition task.

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

Table 3. Percent of target /s/ and percent of target /ʃ/ that were produced correctly by each group.

Group	correct /s/	correct /ʃ/	Group	correct /s/	correct /ʃ/
CI-1	66	84	CI-2	57	77
HA	68	78	CA	71	90

Table 4. The percent of total errors of the most frequent substitutions for /s/.

Group	[ʃ]	[θ]	[f]	[ts]	Group	[ʃ]	[θ]	[f]	[ts]
CI-1	3.7	9.2	**44.4**	12.9	CI-2	4.7	11.9	**30.9**	16.6
HA	**24.4**	13.3	2.2	15.5	CA	15.3	**50**	0	11.5

Table 5. The percent of total errors of the most frequent substitutions for /ʃ/.

Group	[tʃ]	[ts]	[kʃ]	[ks]	[s]	Group	[tʃ]	[ts]	[kʃ]	[ks]	[s]
CI-1	**57.6**	3.8	7.6	11.5	11.5	CI-2	**54.5**	4.5	9	13.6	9
HA	**45.4**	6	0	0	21.2	CA	44.4	0	0	0	**55.5**

Figure 1. The top part of the figure shows the waveform of the fricative /s/ followed by the vowel /u/. The bottom part shows the spectrogram of the same fricative and vowel. The dotted lines show where the beginning and end of the fricative were marked.

Figure 2. Group productions of /ʃ/ and /s/. “S” symbolizes /ʃ/ and “s” symbolizes /s/. CI refers to the group of children with cochlear implants and HA refers to the hearing-age comparison group. Black horizontal bars indicate median values.

Figure 3. Group productions of /ʃ/ and /s/. “S” symbolizes /ʃ/ and “s” symbolizes /s/. CI refers to the group of children with cochlear implants and CA refers to the chronological-age comparison group. Black horizontal bars indicate median values.

Figure 4. Individual children are represented on the x-axis. Participant codes that begin with CI, HA, and CA refer to a child with a cochlear implant, the hearing-age match, and the chronological-age match, respectively. The letters a, i, and u represent the vowels /ɑ/, /i/, and /u/ which were produced after the initial consonant of the word.

Figure 5. Individual children are represented on the x-axis. Participant codes that begin with CI, HA, and CA refer to a child with a cochlear implant, the hearing-age match, and the chronological-age match, respectively. The letters a, i, and u represent the vowels /ɑ/, /i/, and /u/ which were produced after the initial consonant of the word.

Figure 6. Individual children are represented on the x-axis. Participant codes that begin with CI, HA, and CA refer to a child with a cochlear implant, the hearing-age match, and the chronological-age match, respectively. The letters a, i, and u represent the vowels /ɑ/, /i/, and /u/ which were produced after the initial consonant of the word. “3” refers to the vowel /ɝ/.

Figure 7. Individual children are represented on the x-axis. Participant codes that begin with CI, HA, and CA refer to a child with a cochlear implant, the hearing-age match, and the chronological-age match, respectively. The letters a, i, and u represent the vowels /ɑ/, /i/, and /u/ which were produced after the initial consonant of the word.

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Figure 8. Individual children are represented on the x-axis. Participant codes that begin with CI, HA, and CA refer to a child with a cochlear implant, the hearing-age match, and the chronological-age match, respectively. The letters a, i, and u represent the vowels /ɑ/, /i/, and /u/ which were produced after the initial consonant of the word.

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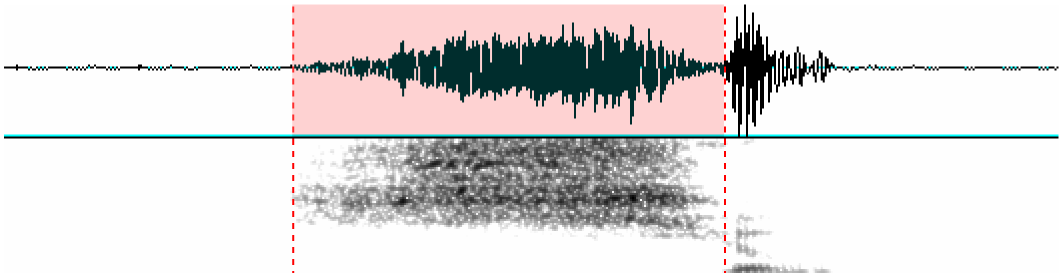

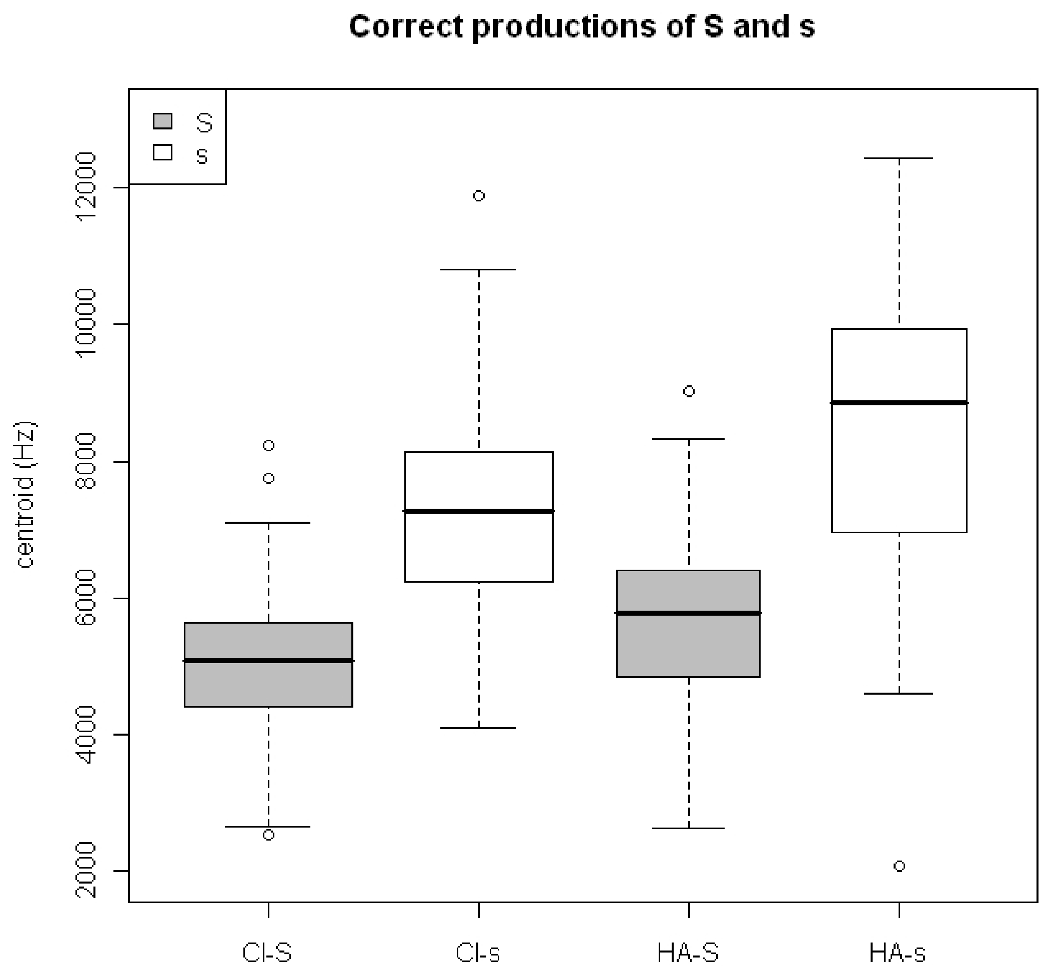
Correct productions of S and s
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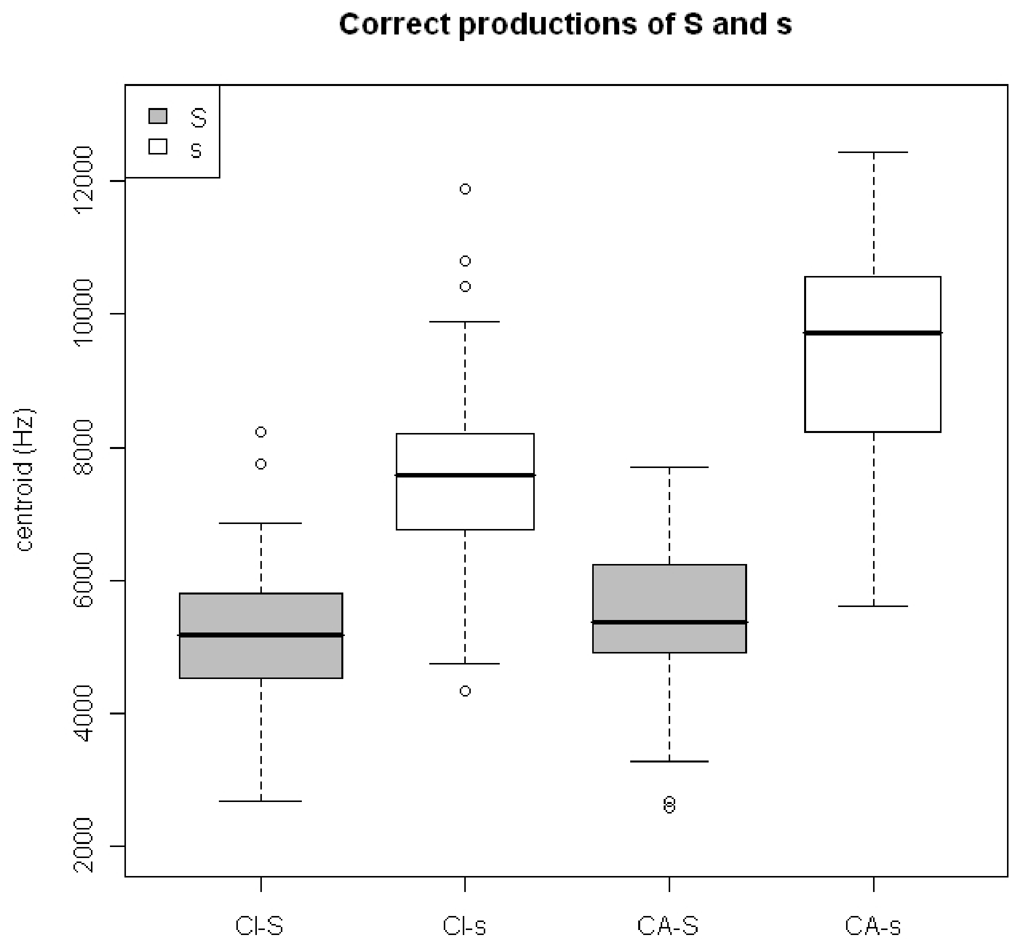
s
centroid (Hz)
2000
4000
6000
8000
10000
12000
CI-S
CI-s
HA-S
HA-s


Correct productions of S and s
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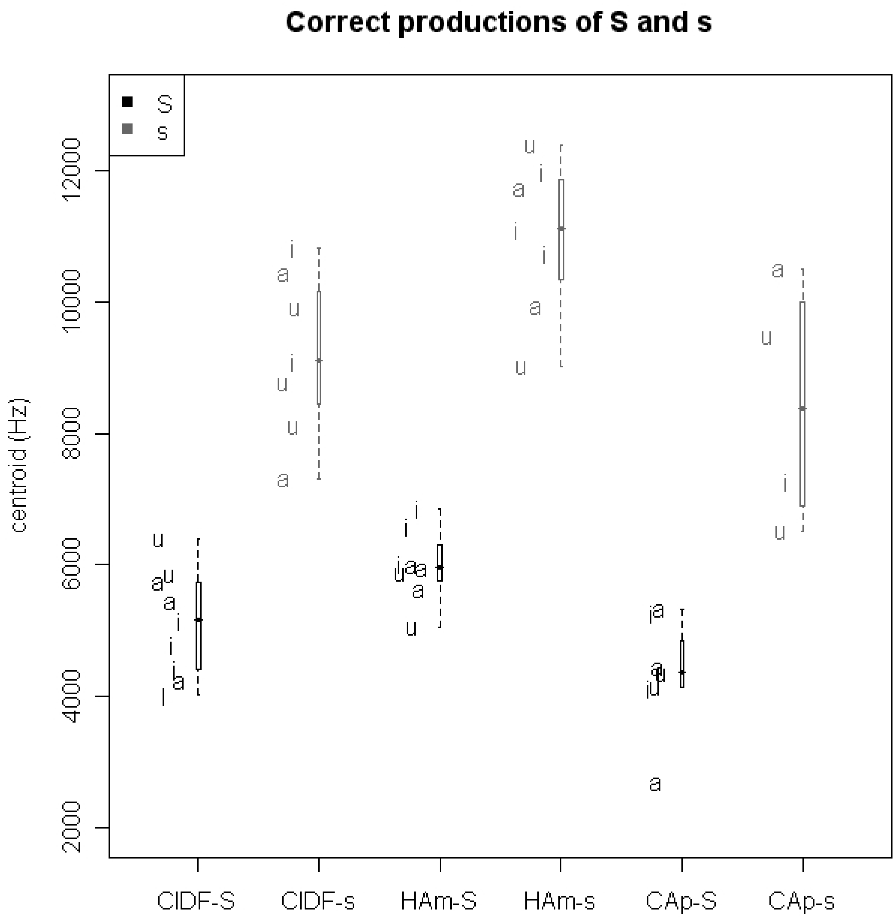
s
centroid (Hz)
2000
4000
6000
8000
10000
12000
CI-S
CI-s
CA-S
CA-s



Correct productions of S and s
S
s
centroid (Hz)
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4000
6000
8000
10000
12000
ClDF-S
ClDF-s
HAm-S
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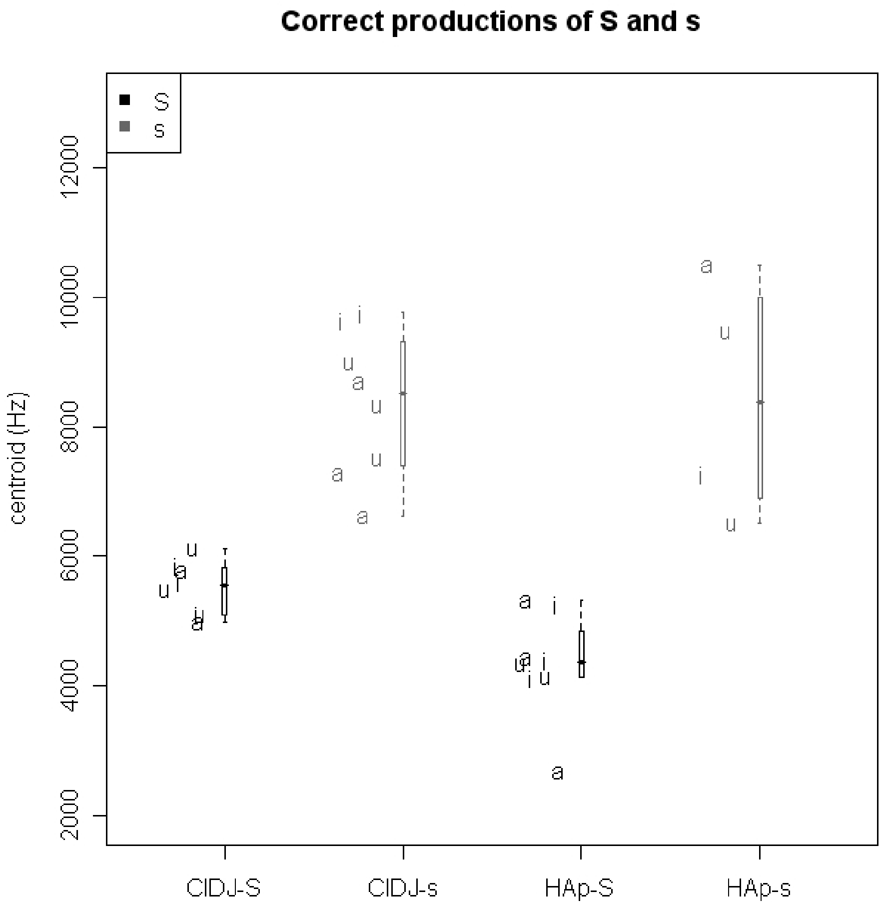
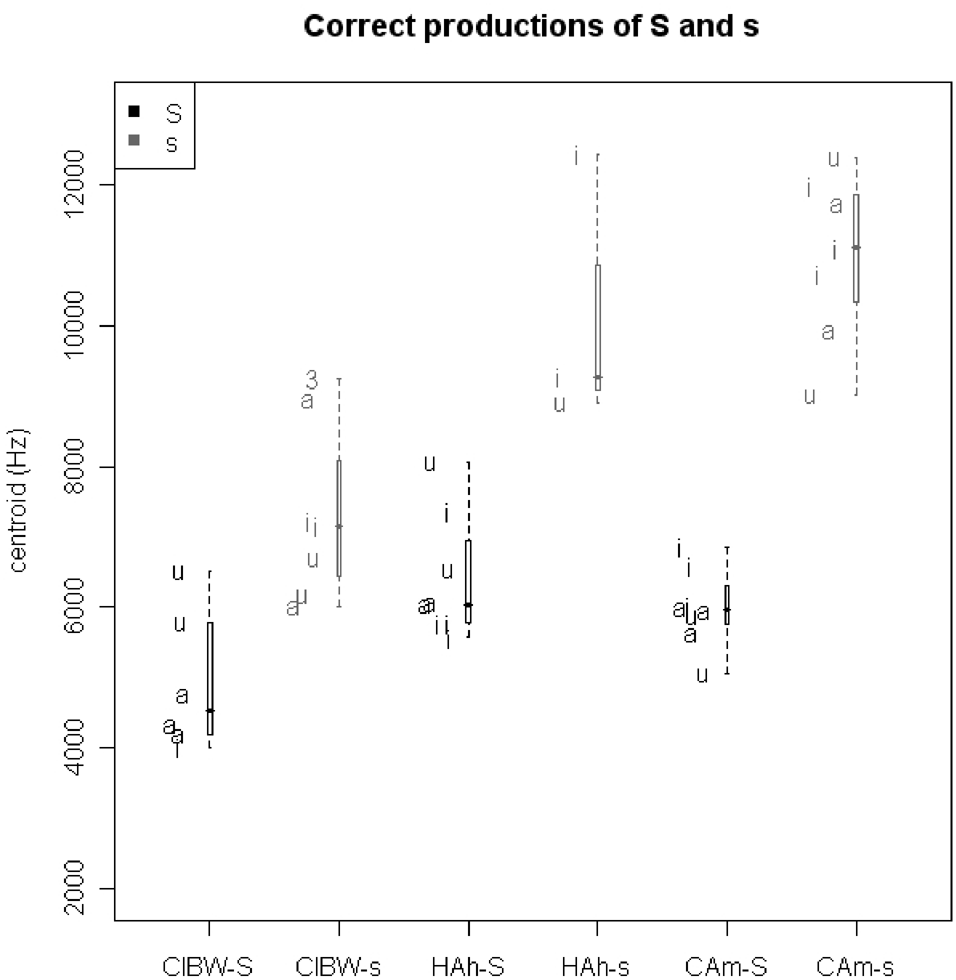
CAp-S
CAp-s


Correct productions of S and s
S
s
centroid (Hz)
2000
4000
6000
8000
10000
12000
ClDJ-S
ClDJ-s
HAp-S
HAp-s


Correct productions of S and s
S
s
centroid (Hz)
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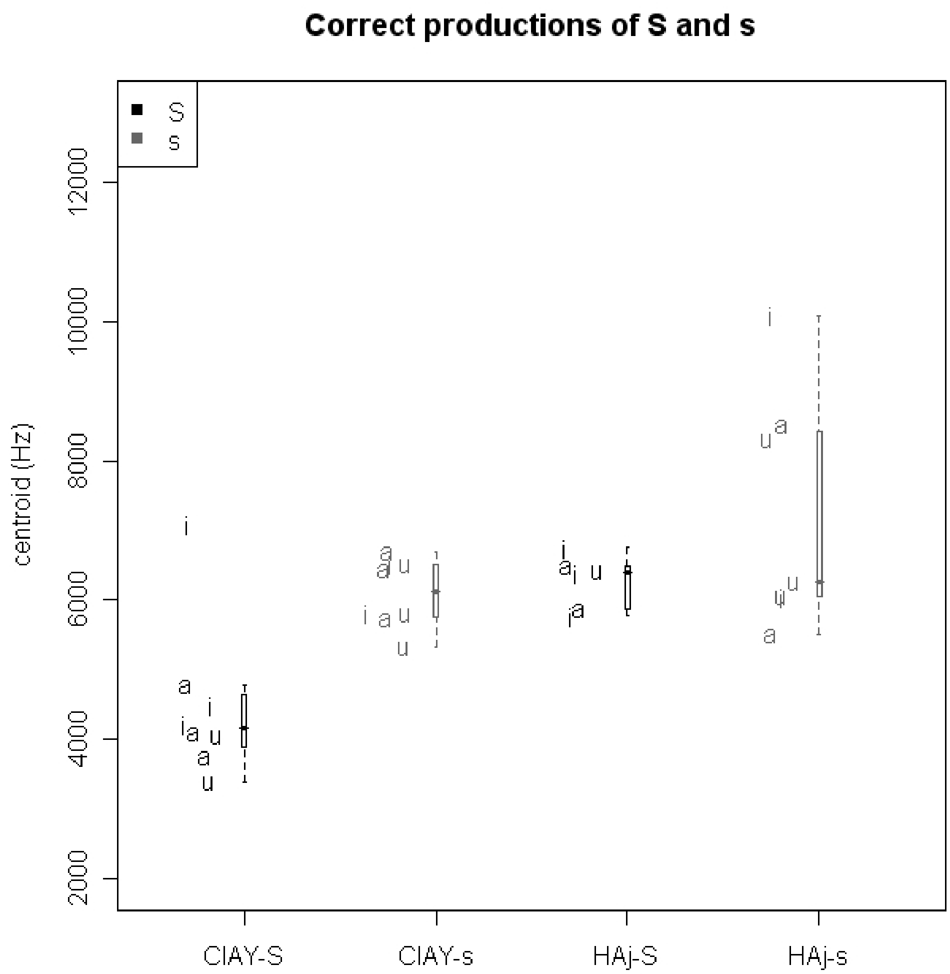
4000
6000
8000
10000
12000
ClBW-S
ClBW-s
HAh-S
HAh-s
CAm-S
CAm-s


Correct productions of S and s
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s
centroid (Hz)
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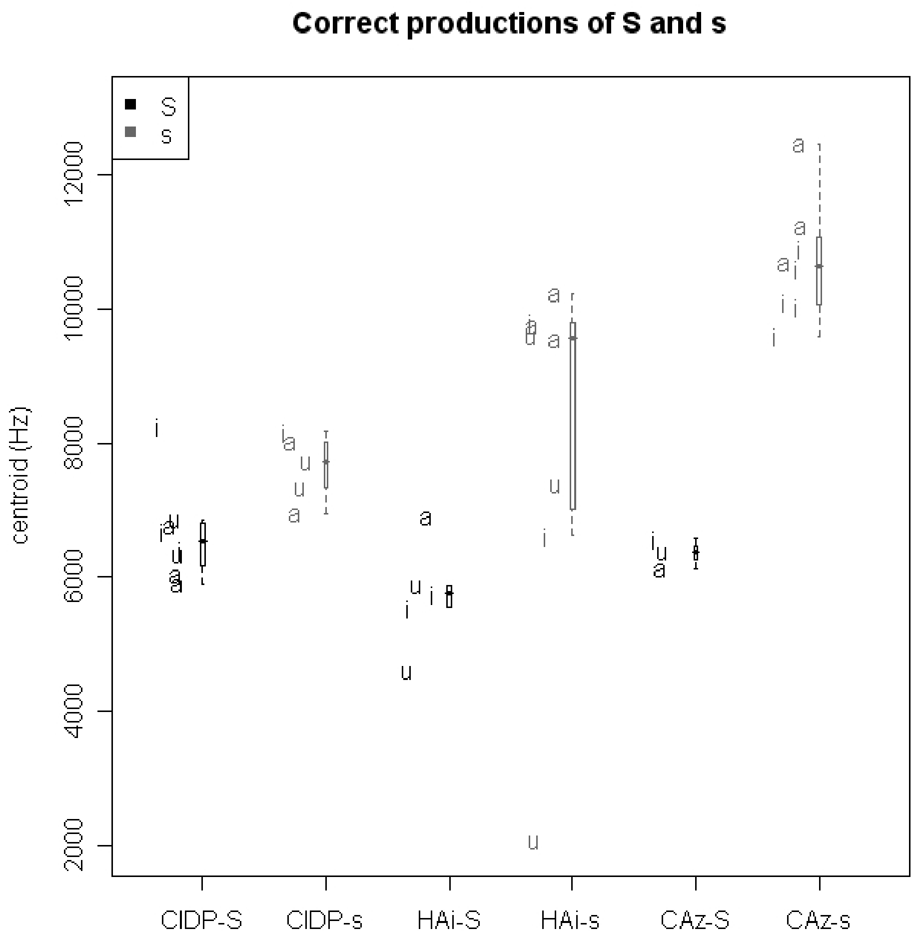
4000
6000
8000
10000
12000
ClAY-S
ClAY-s
HAj-S
HAj-s

44


Correct productions of S and s
S
s
centroid (Hz)
2000
4000
6000
8000
10000
12000
CIDP-S
CIDP-s
HAi-S
HAi-s
CAz-S
CAz-s