Acoustic Analysis of the Speech of Children with Cochlear Implants and Comparison with Hearing Controls

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ABSTRACT

The aim of this study was to analyze the speech of hearing-impaired children with cochlear implants (CI), and compare it with hearing controls (HC). The following variables were analyzed: vowels (F1 and F2), fricatives /s/ and /ʃ/ (spectral differences), and affricates /ts/ and /tʃ/ (total duration and timing of stop-fricative components). There were 18 elementary-school children in each group, matched for age and sex. Acoustic analysis revealed differences between the two groups in all measured variables. Contrary to expectations, the vowel space spanned by the CI children was not much smaller than that of the HC, the significant difference being along the front-back axis (F2). As expected, fricatives were more clearly separated, with respect to noise frequency, in HC than in the CI group. Most CI children substituted fricatives or stops for affricates, and the total duration of those substitutes was significantly longer than the duration of HC's affricates.

1. INTRODUCTION

Cochlear implants have prooven to be very beneficial in rehabilitation of the hearing-impaired. Comparative studies have shown that they are very efficient aids in the reintegration of the profoundly deaf into the hearing world, and that they provide a good foundation for improvement of voice quality, intelligibility and speech production in prelingualy impaired [1, 2, 3] as well as in postlingualy deafened children and adults [4, 5]. The effectiveness of cochlear implants is most frequently tested by means of listening and comprehension tests and/or by analysis of the speech of their users [1, 6, 7]. It has been shown that compared with matched hearing-aid users, children with cochlear implants have better voice quality and overall intelligibility [3, 8]. Various variables have been found to affect the rehabilitation outcome, among which age at implantation and duration of therapy seem to be of great, but not exclusive importance [9, 10, 11].

The aim of the research presented here was to analyze the speech of the children with cochlear implants and compare it with the speech of matched non-impaired controls. We focused on three categories of sounds in Croatian: vowels, fricatives and affricates. All five vowels were included in the test material: high front /i/, high back /u/, mid front /e/, mid back /o/ and low central /a/. Of the five fricatives in Croatian we chose the voiceless alveo-dental /s/ and the palatal /ʃ/. Of the five affricates we chose the voiceless alveo-dental /ts/ and the palatal /tʃ/. Our hypotheses were that (a) the vowel space of the implanted children would be smaller than that of the hearing controls; (b) fricatives /s/ and /ʃ/ of the implanted children would not be as clearly separated; and (c) that affricates would reveal a different stop-fricative pattern.

2. MATERIALS AND METHODS

Two groups of **children** participated in the study. In the group of children with cochlear implants (CI) there were 10 girls and 8 boys. Their age ranged from 8 to 14 (mean: 10.3). The onset of deafness was prelingual. All children had been profoundly deaf before the surgery and had been fitted with hearing aids. At the time of testing, their pure-tone audiograms (with the cochlear implant in place) were between 35 and 50 dB HL (3-frequency mean: 37 dB). Age at implantation ranged between 3:1 and 11:7 years (median: 7:8). Total therapy duration ranged from 1:11 to 9:11 years (median: 5:11). The duration of preoperative rehabilitation ranged between one month and seven years. All children were attending elementary school at the SUVAG Polyclinic for the rehabilitation of speech and hearing, and were included in the Verbotonal method of rehabilitation (based on the auditory verbal approach). None had any psychological or neurological disorders. The hearing controls (HC) were matched for age and sex. None had any hearing or other impairments or disorders. All were attending a regular elementary school in Zagreb.

The **recordings** were done in a relatively quiet classroom in their respective schools. Instructions were given orally. CI children were accompanied by their therapists during the recording session, to make sure that they understood the task. The recording session consisted of four parts. The children told a story on the basis of a series of cartoons, named pictures of everyday objects, presented on 10x8 cm cards by the experimenter, counted from 1 to 10, and repeated after the experimenter 5 words that differed only in the stressed vowel. The words were *pipa*, *pepa*, *papa*, *popa*, *pupa*. In this way all five Croatian vowels, and all Croatian consonants were obtained.

Sony MiniDisc Recorder was used for recording. The selected material was then transferred into a computer (by means of CoolEdit Pro software) and Praat program was used for **acoustic analysis**.

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The five Croatian vowels /i/, /e/, /a/, /o/ and /u/ were obtained from the five words mentioned above. They were analyzed in terms of the first and second formant frequencies (F1 and F2, respectively). Fricatives and affricates were analyzed in words produced by picture-naming and counting. Fricative /s/ was extracted from the words *sedam* (seven) and *deset* (ten). Initial fricative /ʃ/ was extracted from the words /ʃeʃir/ (hat) and /ʃest/ (six). The two /s/s were appended to one another for each speaker and their long-term average spectra were calculated in order to obtain the noise frequency. The same procedure was applied to the two /ʃ/s. Minimum and maximum noise frequencies were calculated for both fricatives. Significance of the differences between the means was tested by the two-tailed *t*-Test, applied to paired or unpaired samples (as appropriate). Affricates /ts/ and /tʃ/ were analyzed in two words per speaker: /suntse/ (sun) and /kutʃa/ (house). Their total duration was measured, as well as the timing of the stop-fricative components (when possible). Average durations and standard deviations were calculated for each group of children. The significance of intergroup differences was checked by *t*-Test.

3. RESULTS AND DISCUSSION

The vowel spaces of CI and HC groups are shown in Figure 1 (open symbols and dashed lines belong to the HC group; full squares and full lines belong to the CI children). The difference can be seen along the front-back axis: the vowels of the CI children are on average more front than of the HC. The differences between F2 frequencies are significant for /a/, /o/ and /u/ ($p < .001$), but not for /i/ or /e/, although the differences appear just as large. The lack of significance may be attributed to the great standard deviation found for these two vowels. On the other hand, the differences between the two groups in F1 frequencies were not significant ($p > .05$), except for /o/ ($p < .05$). These results are contrary to those reported by Kishon-Rabin et al. [2], who found in their subjects with cochlear implants, that perception and production of the five Hebrew vowels (comparable to the Croatian ones) are closer to the hearing children with respect to F2 than wih respect to F1. As it can be seen from the figure, the areas of the vowel spaces are very similar, but since they are further apart in the back and less so in the front, it may be concluded that the area of the CI vowels is smaller than that of the HC. More importantly, however, the shape of the vowel space of our CI children is comparable to that of hearing children. This means that they have mastered the relationships within that space, which we believe to be a good indicator of successful vowel acquisition. Similar results to the one we are reporting here were obtained by Perkell et al. [8].

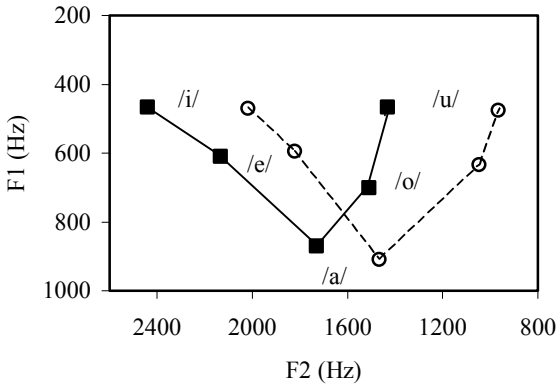

Figure 1: Vowel spaces of the CI (full squares, full lines) and HC (open circles, dashed lines) groups.

Noise frequencies for the two fricatives are shown in Figure 2.

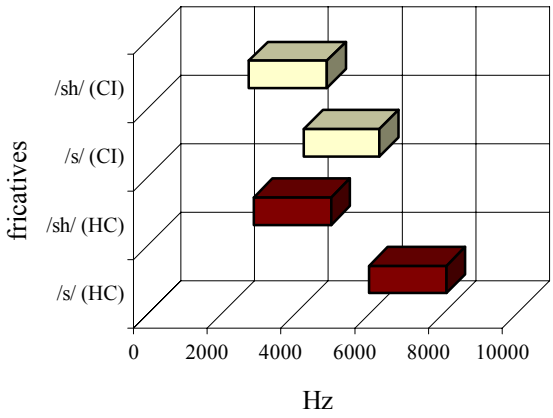

Figure 2: Average minimum and maximum values of noise frequency in two Croatian fricatives (/s/ and /ʃ/) in children with cochlear implants (CI) and hearing controls (HC).

As it can be seen from the figure, these two fricatives could be clearly distinguished on the basis of their noise in the speech of the HC (two bottom bars). Their average /ʃ/ noise frequency was between 2975 and 5074 Hz, and their average /s/ noise frequency was between 5994 and 8092 Hz. On the other hand, minimum /s/ noise frequency (4232 Hz) and maximum /ʃ/ noise frequency (4857 Hz) overlaped in the group of CI children (two top bars). This overlap was caused by /s/ noise being significantly lower than in the HC, and therefore entering into the /ʃ/ noise proper. Both minimum and maximum /s/ noise frequencies in the CI group were significantly ($p<.001$) lower than the corresponding boundaries in the HC. There are no significant integroup differences between the minimum and maximum /ʃ/ noise frequencies. Due to the great amount of auditory control necessary for the distinction between these two fricatives, it is not

surprising that their perception and production are difficult. This result is probably also a manifestation of the difficulties in regulating air flow that is characterisic of profoundly hearing imapired children [1].

Affricates were without a doubt the most difficult for the CI children. Both /ts/ and /tʃ/ were substituted by stops, fricatives or fricative-like noise most of the time (Table 1).

	/ts/		/tʃ/	
% response	CI	HC	CI	HC
correct	33	83	11	100
stop	33	-	22	-
fricative	17	17	56	-
fricative-like noise	17	-	11	-

Table 1: Proportion of correct articulations and various substitutions for affricates in cochlear imlanted children (CI) and hearing controls (HC).

It was therefore impossible to analyze stop-fricative timing in this group and only total duration of the sound in the affricate slot was measured. Average duration of the entire affricate position was significantly ($p < .001$) longer in the CI group (186 ms) than in the HC group (139 ms), in spite of the fact that the controls managed to complete the stop-fricative combination in all /tʃ/ occurrences and in 15 of 18 /ts/ slots. That difference in duration corresponds to the results of Horga *et al.* [12], who reported that the rate of articulation of the profoundly deaf children was by 43% slower than that of the hearing unimpaired controls. Analysis of timing revealed that the fricative portion constituted 55.5% of the entire affricate duration, with 44.5% accounted for by the stop portion.

Since the group of children with cochlear implants was very heterogenous with respect to a number of variables, that are generally considered to have effect on the perception and production of speech, we could not make any reliable or valid analyses of possible interactions. However, in every part of the study we did look for the children that were the closest to the hearing controls in their performance. We did not find any one child who was the closest to hearing controls in all three categories of sounds. Five of them were among the best in two of the three categories, and four more children were the closest in one category. None of the children with cochlear implants were within one standard deviation of the controls in all vowels. Those who were the closest in four out of five vowels (not necessarily the same vowels) were aged between 11:6 and 11:9 (two girls and a boy). Two of the children were implanted at age 7 (below the median), one at age 11:3 (above the median), and their total rehabilitation ranged between 4:8 and 6 years (below or near the median). One of the girls also came closest to the fricative noise values for /s/, and another boy for /ʃ/. The differences between those two children were 2:2 years in chronological age, 16 months in total rehabilitation (one below, on just above the median) and 2:7 years in the age at implantation (both below the median). The greatest variability among the implanted children was with respect to the quality of affricate production. Only one girl produced both affricates. Her age at the time of testing was 13:8, she had been implanted at the age of 6 and she had spent a total of 7:8 years in therapy. She is one of the oldest in her group and well above the median (5:11) with regard to total time spent in therapy. Of the six additional children who produced one of the two affricates, all but one were above he median with respect to age at implantation and with respect to total rehabilitation. Their age ranged from 9:4 to 14 years. The two children who were also the closest in affricate duration to the hearing controls were 10:10 years old. The boy was implanted at the age of 9:11 and the girl at the age 10:4. They differed in total rehabilitation time by only 6 months (7:11 and 7:5 years, respectively). These results allow some speculation that older children, that had been involved in therapy for the longest periods of time show better results than the ones whose therapy has not lasted as long. This was also found in an earlier study that compared the voice quality and intelligibility of children with cochledar implants and classical hearing aids [3], but there are other studies that report that age is not necessarily inversely proportional to the outcome [13].

4. CONCLUSIONS

The results of this study have revealed several differences between the speech of children with cochlear implants and their matched non-impaired controls. Although there are significant differences in the F2 values, that are a manifestation of the more front position of the vowel space in the speech of the children with cochlear implants, the relationship among the vowels seems to be well established and it corresponds to the pattern of the hearing children's vowel space. Children with cochlear implants do not make a clear distinction between the fricatives /s/ and /ʃ/. The noise frequency of their /ʃ/ corresponds approximately to that of the hearing controls, but the noise frequency of their /s/ is significantly lower and overlaps with the higher ends of the /ʃ/ noise range. Affricates /ts/ and /tʃ/ are more frequently substituted by stops, fricatives or fricative-like sounds than produced correctly. Those substitute sounds, albeit less complex articulatory gestures than true affricates produced by hearing controls, are significantly longer. It seems that total rehabilitation time affects the production outcome more than age at implantation. This confirms the importance of therapy, particularly by oral methods, as a prerequisite for successful rehabilitation.

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