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Acoustic analysis of the speech of children with cochlear implants: A longitudinal study

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Abstract
The aim of the study was to analyse the speech of the children with cochlear implants, and compare it with the speech of hearing controls. We focused on three categories of Croatian sounds: vowels (F1 and F2 frequencies), fricatives (noise frequencies of /s/ and /ʃ/), and affricates (total duration and the pattern of stop-fricative components in /ts/ and /tʃ/). Eighteen implanted children, aged between 9;5 and 15;2 years participated in the study. All had been profoundly hearing impaired before implantation. Three recordings per child were made over a 20-month period. The hearing controls were matched for age and sex. Implanted children had a smaller and fronted vowel space, their /s/ and /ʃ/ noise frequencies overlapped, affricates were longer, with a high proportion of incorrect productions and substitutions. With time, there was a small but steady overall improvement in all categories. Early intervention (rehabilitation and implantation) are crucial for good speech acquisition.

Keywords: *Cochlear implants, children, fricatives, vowel space, affricates, speech production*

Introduction

Cochlear implants are hearing aids that change the quality of life of their users in ways that were unthinkable just a few decades ago. Together with appropriate and consistent auditory-oral therapy they provide severely to profoundly hearing impaired persons with the choice of functioning and interacting in the hearing world more easily. Studies have shown that, provided that the criteria and guidelines for patient selection are observed, they are beneficial for the improvement of voice quality, intelligibility, speech perception and production in prelingually impaired (Tobey, Geers, & Brenner, 1996; Kishon-Rabin et al., 2002; Mildner, Šindija, & Horga, 2003; Calmels et al., 2004) as well as in postlingually deafened children and adults (Matthies & Svirsky, 1996; Ito, Suzuki, Toma, Shiroma, & Kaga, 2002; Välimaa, Määttä, Löppönen, & Sorri, 2002a, b). 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 (O'Donoghue, Nikolopoulos, Archbold, & Tait, 1999; Richter, Eissele, Laszig, & Lohle, 2002; Houston, Pisoni, Iler Kirk, Ying, & Miyamoto, 2003; Calmels et al., 2004). Various factors have been found to affect the rehabilitation outcome, among which age at implantation and duration of therapy seem to be of great, but

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not exclusive importance (Gordon, Daya, Harrison, & Papsin, 2000; Pisoni, 2000; Tait, Luttman, & Robinson, 2000; Dowell et al., 2002; Surowiecki et al., 2002; Mildner & Liker, 2003; Mildner et al., 2003; Nikolopoulos, Gibbin, & Dyar, 2004; Vlahović & Šindija, 2004).

An earlier acoustic analysis of the speech produced by Croatian children with cochlear implants (Mildner & Liker, 2003) has shown that there were several types of problems, depending on the sound category. Compared with the non-impaired children, their affricates were significantly longer and were more often substituted by fricatives, stops, or even unidentifiable fricative noise, than pronounced correctly. In their speech they did not distinguish sufficiently between the fricatives whose cues were noise frequency. Their vowels were fronted, i.e., had higher second formant frequencies. The aim of the research presented here was to monitor their progress in the acquisition of these sound categories during regular rehabilitation, that proceeded by means of the Verbotonal method at the SUVAG Polyclinic, by recording their production of the same speech material at regular intervals. All five Croatian 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 six 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 initially smaller and fronted vowel space of the implanted children would expand and shift backward; (b) the separation of fricatives /s/ and /ʃ/ would become clearer; and that (c) affricates would become shorter and the proportion of correct targets would increase.

Material and method

Subjects

Two groups of subjects participated in the study. Group 1 were 18 children with cochlear implants (ten girls and eight boys). Their data are shown in Table I. Group 2 were a control group, consisting of the equal number of unimpaired children matched for sex, age and education level. All children with cochlear implants had been profoundly deaf (prelingually) before implantation. They had been fitted with stereophonic hearing aids and had been included in the Verbotonal method of rehabilitation at the SUVAG Polyclinic for the rehabilitation of speech and hearing in Zagreb, where they were attending elementary school. With the cochlear implant in place, their pure-tone audiograms were between 35 and 50 dB HL (3-frequency mean: 37 dB).

Speech material

Children with cochlear implants were recorded at the SUVAG polyclinic during their regular one-on-one therapy sessions at three time points: in December 2002 (12/02), in April 2003 (04/03) and in December 2003 (12/03). The control children were recorded at the elementary school Gustav Krklec in Zagreb. Sony MiniDisc Recorder was used for recording. Speech samples were then transferred to a notebook type computer by means of the Cool Edit Pro software and acoustic analysis was done in Praat.

Speech material was elicited by presenting picture cards for naming everyday objects, by having the children repeat nonsense syllable combinations *p**i**pa*, *p**e**pa*, *p**a**pa*, *p**o**pa*, *p**u**pa*, and by having them read out numbers 1 through 10 presented on cards in random order. Production of the five Croatian vowels was analysed in terms the first and second formant

Table I. Patient data at the time of last recording.

Patient	Age	Age at start of rehab.	Age at implantation	Postoperative rehab. time	Total rehab. time	Implant side
AB	13;3	7;1	11;11	1;4	6;2	R
AČ	12;11	2;11	11;7	1;4	10;0	R
AL	12;11	7;8	11;7	1;4	5;3	R
AP	10;9	3;6	3;11	6;10	7;3	R
AR	9;5	6;2	7;4	2;1	3;3	R
DK	10;0	2;9	7;6	2;6	7;3	R
EA	12;8	5;5	6;11	5;9	7;3	L
IB	14;10	6;0	6;0	8;10	8;10	R
ID	10;6	3;3	5;1	5;5	7;3	L
KŽ	12;0	2;10	9;10	2;2	9;2	L
LD	9;7	3;5	7;0	2;7	6;2	R
LR	10;0	1;10	7;6	2;6	8;2	R
ME	12;3	4;4	10;0	2;3	7;11	L
RH	11;9	3;6	10;0	1;9	8;3	R
SA	15;2	4;0	9;6	5;8	11;2	R
TM	9;10	2;4	7;4	2;6	7;6	L
TMA	12;2	3;7	10;8	1;4	8;7	R
ZR	12;8	6;7	6;7	6;1	6;1	R
Range	9;5–15;2	1;10–7;8	3;11–11;11	1;4–8;10	3;3–11;2	
Median	12;1	3;7	7;6	2;6	7;5	

frequencies (F1 and F2, respectively) and presented as a formant-defined vowel space. For that purpose the F1 and F2 frequencies of the vowels /i/, /e/, /a/, /o/ and /u/ embedded in otherwise identical nonsense words were read off from the spectrograms generated by Praat.

Fricatives /s/ and /ʃ/ were analysed in terms of their noise frequencies, by examining the recordings of the words /sedam/ (seven) and /deset/ (ten) for /s/ and the words /ʃeʃir/ (hat) and /ʃest/ (six) for /ʃ/, elicited by naming objects and numbers. The two /s/s as well as the two /ʃ/s of each speaker were appended to each other. Their respective long-term average spectra were calculated in order to obtain the noise frequency. Minimum and maximum values of noise frequency for both fricatives were calculated. Affricates /ts/ and /tʃ/ were analysed for total duration and the pattern of stop-fricative components by examining the recordings of words /suntse/ (sun) for /ts/ and /kutʃa/ (house) for /tʃ/, elicited by naming objects.

Results and discussion

Vowels

Data on F1 and F2 frequencies of CI children and controls are presented in Figure 1, as overlaid curves spanning the respective vowel spaces.

As it can be clearly seen, the vowel spaces of CI children are fronted with respect to the hearing controls, with consequently higher F2 frequencies. This is true overall, for the entire spaces, but on closer inspection it may be noticed that the fronting is more pronounced for the back vowels /u/ and /o/ as well as for the central /a/. The differences between F2s of the control group and the CI group at all three time points are statistically significant ($p<.01$) for these three vowels. With the exception of the difference in F2

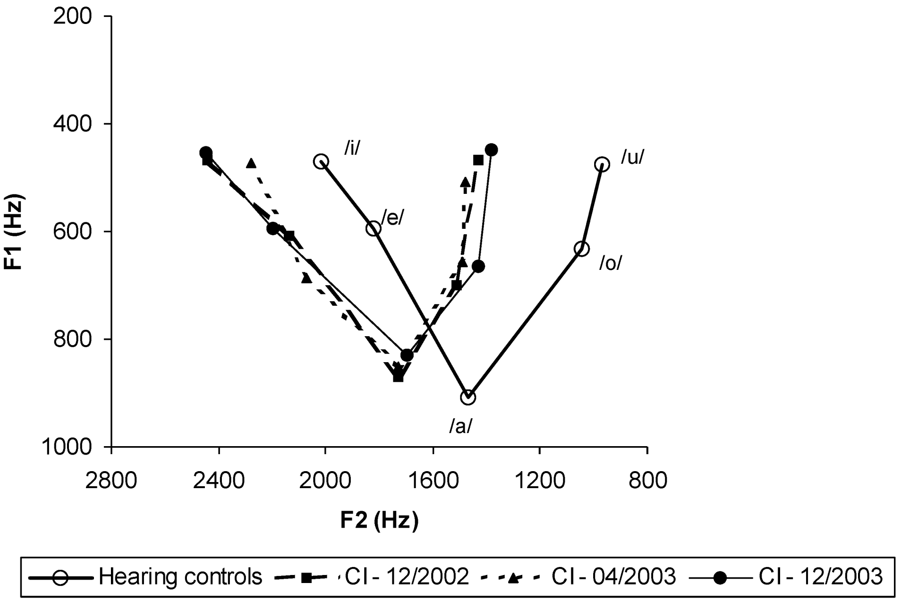

Figure 1. Formant-defined vowel spaces of CI children at the three different time points, compared with hearing controls.

frequency for /i/ and /e/ between the control group and CI at the third time point ($p<.05$), the differences between the controls and CI children are not statistically significant ($p>.05$) for these two front vowels. These relations indicate that the vowel space of the CI children is on average smaller than that of controls. With respect to F1 frequencies, i.e., differences in the vertical position of the tongue along the open-close dimension, there are no consistent significant differences between the hearing children and the CI subjects: the mean F1 frequency of the CI group is significantly lower for /a/ at the second and third time point than the mean F1 frequency of the control group, indicative of the more close articulation, i.e., again smaller vowel space. The only two other instances of significant differences between F1 of CI children and hearing controls found for /e/ at the second time point and for /o/ at the first time point are in agreement with Tobey et al.'s (1996) data showing that mid-vowels are more difficult for hearing impaired children to produce correctly than the high or the low ones. There were no consistent statistically significant differences among F1 and F2 frequencies of CI children at different time points.

Kishon-Rabin et al. (2002) found in their subjects with cochlear implants, that perception and production of the five Hebrew vowels are more similar to the hearing children with respect to F2 than with respect to F1 frequency. The fronting of the vowel space in CI children may possibly be explained by the tendency of therapists, family and children themselves to move articulation to where it can be more visible, i.e., shift it toward the front of the mouth. Välimaa et al. (2002a) found that in cases of vowel confusions cochlear implant users have a bias toward higher frequencies for at least two years after implantation. Our data are in large part in agreement with that. With the exception of /a/, where the mean F1 frequency of CI children at all time points is lower than that of controls, mean F1 and F2 frequencies of all vowels pronounced by the CI children were higher (albeit not always reaching significance) than those of controls. In the only three instances when they were lower the difference was within 20 Hz. We found the shape of the vowel space of the CI children to be comparable to that of unimpaired children, suggesting that they have mastered the relationships within that space. We believe this to be a good indicator of successful vowel acquisition. Similar results to the ones we are reporting here were obtained by Perkell et al. (2001). Another point can be made about the progression of the CI group. There was a trend toward expanding the vowel space further back at the last time point (lowering the F2 frequencies, while at the same time keeping the fronted position of the front vowels) compared with the first two time points, but the change was not large enough to reach statistical significance. It seems that in the process of acquiring the target vowel space the existing space will be expanded first and then shifted back into its position found in the unimpaired population. Subsequent analyses of the same children may shed more light on that issue.

Fricatives

The noise frequencies of Croatian fricatives /s/ and /ʃ/ obtained from CI children at three different points and those of hearing controls are shown in Figure 2.

There is a clear separation between the noise frequencies of the two fricatives in the control group (bottom two bars). Their mean /s/ noise frequency was between 5994 and 8092 Hz, and their mean /ʃ/ noise frequency was between 2975 and 5074 Hz. On the other hand, minimum /s/ noise frequency for the CI group at the three time points was 4232 Hz, 4925 Hz and 4689 Hz, respectively, and obviously overlapped with the maximum /ʃ/ noise frequency (4857 Hz, 5428 Hz and 5513 Hz, respectively) at all time points. This overlap was caused by /s/ noise being significantly lower than in the HC, and therefore entering into the /ʃ/ noise proper. The following differences were found to be statistically significant ($p < .05$) for the /s/ noise frequency: (a) controls vs. CI at all time points with respect to lower end of the noise range; (b) controls vs. CI recorded on 12/02 and 12/03, with respect to the higher end of the noise range; (c) 12/02 vs. other two time points with respect to the higher end of the noise range. With regard to /ʃ/, the only significant difference was in the CI group between the recordings made in 12/02 on the one hand, and those made at the two later time points with respect to the higher end of the noise range. Obviously, the culprit for

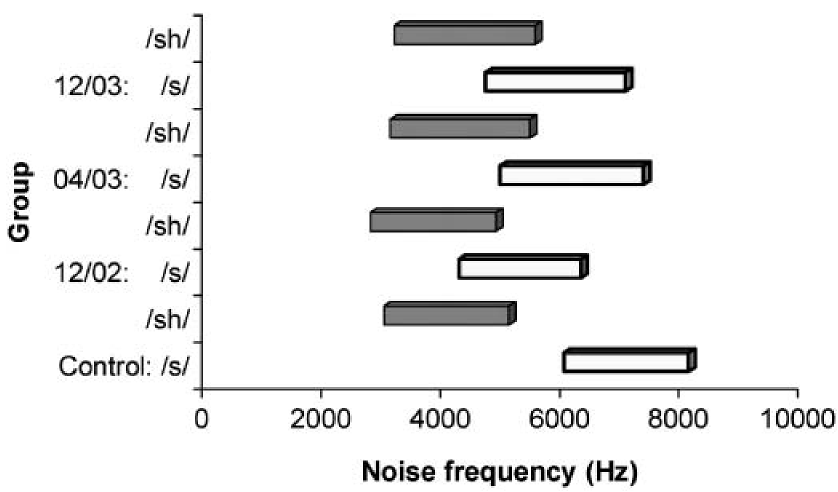

Figure 2. Noise frequencies of /s/ and /ʃ/ for CI children at three recorded time points and for controls.

the overlap is the inability of the CI children to produce /s/ with noise high enough to separate it from /ʃ/. After the initial improvement found at the second time point compared with the first one, the distinction still remains problematic. That is probably due to the great amount of auditory control necessary for the distinction between these two fricatives. Matthies and Svirsky (1996) found in their adult postlingually deafened cochlear implant user that even switching the implant off for as little as an hour resulted in the subject's inability to keep the distinction between /s/ and /ʃ/. This result is probably also a manifestation of the difficulties in regulating air flow that is characteristic of profoundly hearing impaired children (Tobey et al., 1996). Fricative [ʃ] is probably one of the most over-represented segments in the speech of profoundly hearing impaired children. They frequently substitute it for /s/, /tʃ/, and /ʒ/ in addition to using it in its right place.

Affricates

Affricates were the most difficult of the analysed phonemes, which is not surprising given the complexity of their articulation and timing. The duration data for /tʃ/ and /ts/ for CI children at three time points and for hearing controls are presented in Figure 3.

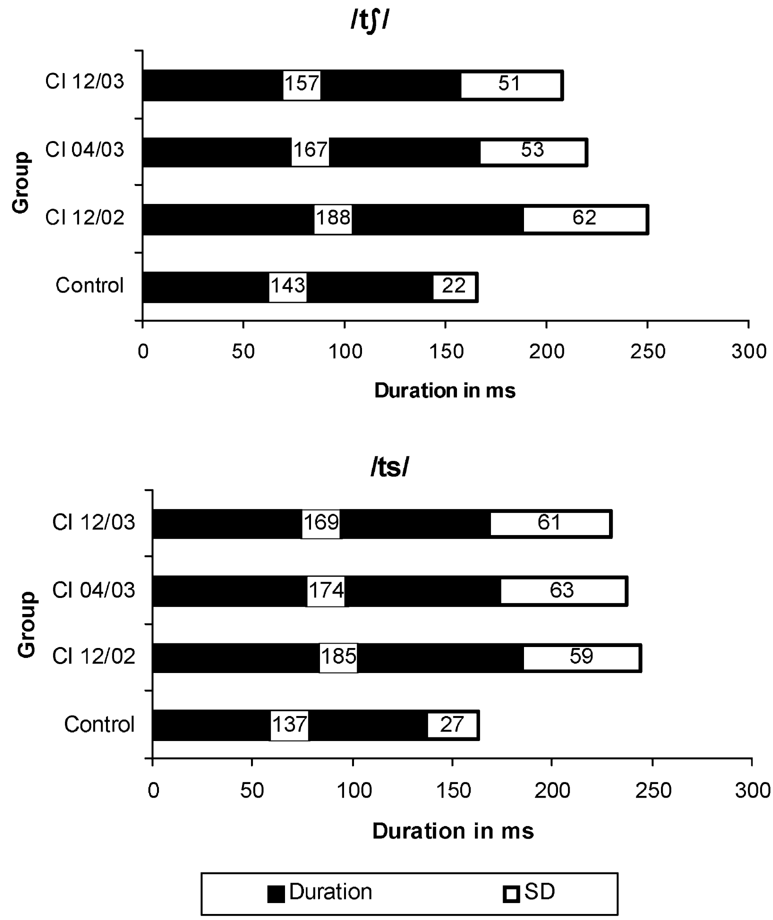

Figure 3. Duration (and standard deviations) of affricates /tʃ/ and /ts/.

Obviously, CI children take longer to produce the affricate (or another sound in its place, see below for analysis) than unimpaired children, but the duration steadily decreases with therapy. This decrease is greater in /tʃ/. The difference in mean duration decreases by about 69% (from 45 ms at the first time point to 14 ms at the third). On the other hand, the difference in mean duration at different time points for /ts/ decreases by only 33% (from 48 ms at the first time point to 32 ms at the third). Statistically significant ($p<.05$) differences were found between controls and CI subjects at all time points for /ts/, whereas for /tʃ/ the CI children took significantly longer than the hearing controls to produce the affricate or its substitute only at the earliest time point. At the third time point the duration is already significantly shorter than that recorded at the first time point. Although the relatively small number of actually produced affricates in the CI group does not allow serious statistical analysis, it must be mentioned that the timing is considerably different between the two groups. In the control group the stop portion constituted, on average, 44.5% of the entire affricate duration (51% in /tʃ/ and 38% in /ts/). In the CI group the stop portion was longer (between 52 and 60% in /tʃ/ and between as much as 72 and 78% in /ts/). This is in line with the generally more tense articulation of profoundly hearing impaired children compared with the unimpaired population.

Production patterns of target affricates /tʃ/ and /ts/ are presented in Table II. The data are based on the auditory assessments of 20 trained phoneticians. We felt the need to carry out this independent perceptual test because of discrepancies in the judgements of what the CI children were actually saying among the present authors. In the row "other affricate" the most frequent were mutual substitutions of the two observed affricates, with more frequent substitutions of /tʃ/ for /ts/ than vice versa.

There were statistically significant differences ($p<.05$) between controls and CI children at all time points in terms of the percentage of correct responses. In the CI group there were no statistical differences among time points for any of the realizations of /tʃ/, but there was a steady increase in the proportion of correctly produced targets (from 21.94 to 28.62% correct targets). The most frequent substitutions were stops, followed by fricatives, but the differences in proportions were not statistically significant ($p>.05$). Affricate /ts/ was more difficult for the children. Even in the control group some of their renditions (16.67%) were judged as incorrect by the listeners. In the group of CI children, at the third time point the difference between the number of correct /tʃ/ and /ts/ targets was statistically significant

Table II. Production patterns of target affricates /tʃ/ and /ts/ (in %).

	Controls	12/02	04/03	12/03
/tʃ/				
correct	100	21.94	23.61	28.61
other affricate	0	.83	5.56	.56
stop	0	32.78	36.67	24.44
fricative	0	27.50	21.67	29.17
other	0	16.94	12.50	17.22
/ts/				
correct	83.33	6.39	13.89	3.89
other affricate	0	9.44	8.33	21.94
stop	0	56.67	53.06	44.44
fricative	16.67	15.00	16.39	21.11
other	0	12.50	8.33	8.61

(p=.019). The most frequent substitutions for /ts/ were stops. At the first and second time point they were significantly more frequently found than any other realisation (56.67 and 53.06%, respectively). At the third time point, however, their proportion is significantly smaller than at the first (44.44%). Although the number of correct /ts/ realisations remains low, it is encouraging to note that there is a significant increase in the proportion of "other affricate" (namely /tʃ/ in place of /ts/) at the third time point. If the two rows are taken together (correct+other affricate) the steady increase in the proportion of affricates becomes clear (from 15.83 to 25.83% for /ts/ and from 22.77 to 29.17% for /tʃ/). This indicates that the children are mastering the manner-of-articulation feature. We expect that the necessary shift in place of articulation will follow.

General discussion

As it can be clearly seen from Table I, the group of children with cochlear implants was heterogenous with respect to a number of variables, including those that are generally considered to have major impact on the perception and production of speech (Gordon et al., 2000; Pisoni, 2000; Tait et al., 2000; Surowiecki et al., 2002; Nikolopoulos et al., 2004; Vlahović & Šindija, 2004). Therefore, we could not make any reliable or valid analyses of possible interactions. However, for every analysed sound category we did look for the children whose performance matched that of the unimpaired subjects. No child corresponded to hearing controls in all three categories of sounds.

By plotting individual data for all children at all time points against the mean data for controls for each vowel we found that of the 18 children involved in the study 11 were at some time point and for some vowel the most similar to the controls. Two children were closest for three vowels (AL for /i/ and /a/ at the first time point and /e/ at the third time point; AR for /i/ and /u/ at the first time point and for /e/ at the second time point). One child (AB) was the most similar for two vowels (/a/ at the second time point and /o/ at the third time point). The remaining eight children's data (DK, ID, AP, IB, RH, KŽ, LR and AČ) corresponded to the controls for one vowel/time point. As it can be seen from the summary of patient data in Table I, the two most successful children with respect to vowels were implanted late (just below or well above median) and had a relatively short period of postoperative rehabilitation (1;4 and 2;1 years). Children who were implanted at an earlier age, e.g., AP, ID, IB did not do as well.

In the category of fricatives, the analysis of the /s/ and /ʃ/ noise frequencies has revealed that only one girl, ZR, produced well separated fricatives at all three time points. At the time of the last recording she was 12 years and 8-months-old. She was implanted at the age 6;7, with virtually no prior rehabilitation period, and her postoperative rehabilitation lasted 6 years and one month. KŽ had non-overlapping noise frequencies at the first and second time point. He was implanted at 9;10 and at the time of last recording he was 12-years-old, having had a total of 9;2 years of therapy. EA, AR, DK, IB and ID produced fricatives without noise frequency overlap at one time point each.

The greatest variability among the implanted children was with respect to affricate production. Only one girl produced affricates at all time points (IB). Her /tʃ/ was judged as correct 95% of the time at each time point, but she substituted /ts/ for /tʃ/ at all time points (75% at the first and third time point and 100% at the second). In spite of latter substitutions no other child was as consistent. Her /tʃ/ durations were within one SD of the mean of controls at all time points. The /ts/ target durations at the first two time points were also within one SD of the controls' mean, and the only exception was the last time point at which her /ts/ target was shorter (84 ms). Her age at the time of last testing was 14;10, she had been implanted at the age of 6 (third youngest in the group) and she had spent a total of 8;10 years in therapy. She is one of the oldest in her group and well above the median (7;5) with regard to total time spent in therapy.

While age at implant remains of critical importance for the outcome of the therapy, our results allow some speculation that older children, that had been involved in therapy for longer 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 cochlear implants and classical hearing aids (Mildner et al., 2003), but there are other studies that also report that age is not necessarily inversely proportional to the outcome (Dowell et al., 2002).

It should be kept in mind that the median time of post-implant rehabilitation is only 2;6 years and in terms of age at implant the CI group as a whole can be considered as "late": median age at implant was 7;6 years. As many authors have pointed out, considerable improvements in speech perception and production may by expected for up to 5 years post-implant (Kishon-Rabin et al., 2002; Välimaa et al., 2002a, b; Calmels et al., 2004). So, even in spite of their late start in terms of hearing age we can expect these children to perform better with regular therapy. The results of this study have proven once again the importance of early diagnosis and intervention (therapy and implantation). Moreover, in addition to timeliness, the regularity of therapy has been proven essential. Even short and sporadic breaks in therapy, or failure to use the implant regularly, regardless of their reasons, have had negative effects on the patients' performance, which is in agreement with literature data (Gordon et al., 2000; Vlahović & Šindija, 2004). We suspect that many endogenous and exogenous factors, such as family support, children's cognitive styles and preverbal and nonverbal competencies play very important roles in the outcome of the rehabilitation as has been suggested by a number of authors (Pisoni, 2000; Tait et al., 2000; Surowiecki et al., 2002; Nikolopoulos et al., 2004).

Conclusions

The vowel space of implanted children is smaller than that of hearing controls, and fronted. Back vowels differ more than front vowels with respect to F2. Little significant change has been achieved with rehabilitation. One of the possible reasons for that may be the fact that the five Croatian vowels are sufficiently distant perceptually which allows large allophonic variation.

Noise frequency of /s/ is lower in children with cochlear implants than in unimpaired controls, resulting in overlap with the noise of /ʃ/. Improvement with rehabilitation is slight and slow. Duration of the affricates /ts/ and /tʃ/ is longer in CI children than in hearing controls. This steadily improves with rehabilitation. Pattern of target productions changes with rehabilitation in favour of correct responses or at least correct manner-of-articulation realisations. The direction of errors and substitutions is comparable to those in /s/ and /ʃ/. Affricate /ts/ is more difficult than /tʃ/.

The production of children with cochlear implants improves with rehabilitation. The slow progress may be explained by the relatively late implantation and short post-implant period. This is supported by the trend of the children implanted earlier and undergoing rehabilitation for a longer time to have better articulation. No single implanted child was exceptionally good or bad at all measurement points or in all sound categories.

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References

Calmels, M.-N., Saliba, I., Wanna, G., Cochard, N., Fillaux, J., Deguine, O., & Fraysse, B. (2004). Speech perception and speech intelligibility in children after cochlear implantation. *International Journal of Pediatric Otorhinolaryngology*, *68*, 347–351.

Dowell, R. C., Dettman, S. J., Hill, K., Winton, E., Barker, E. J., & Clark, G. M. (2002). Speech perception outcomes in older children who use multichannel cochlear implants: older is not always poorer. *The Annals of Otology, Rhinology and Laryngology Supplement*, *189*, 97–101.

Gordon, K. A., Daya, H., Harrison, R. V., & Papsin, B. C. (2000). Factors contributing to limited open-set speech perception in children who use a cochlear implant. *International Journal of Pediatric Otorhinolaryngology*, *56*, 101–111.

Houston, D. M., Pisoni, D. B., Iler Kirk, K., Ying, E. A., & Miyamoto, R. T. (2003). Speech perception skills of deaf infants following cochlear implantation: a first report. *International Journal of Pediatric Otorhinolaryngology*, *67*, 479–495.

Ito, K., Suzuki, Y., Toma, M., Shiroma, M., & Kaga, K. (2002). Postlingual collapse of language and its recovery after cochlear implantation. *International Journal of Pediatric Otorhinolaryngology*, *62*, 261–265.

Kishon-Rabin, L., Taitelbaum, R., Muchnik, Ch., Gehtler, I., Kronenberg, J., & Hildesheimer, M. (2002). Development of speech perception and production in children with cochlear implants. *Annals of Otology, Rhinology and Laryngology*, *111*, 85–90.

Matthies, M. L., & Svirsky, M. (1996). Acoustic and articulatory measures of sibilant production with and without auditory feedback from a cochlear implant. *Journal of Speech and Hearing Research*, *39*, 936–946.

Mildner, V., & Liker, M. (2003). Acoustic analysis of the speech of children with cochlear implants and comparison with hearing controls. *Proceedings of the 15th International Congress of Phonetic Sciences*, 1–9 August, Barcelona, pp. 2377–2380.

Mildner, V., Šindija, B., & Horga, D. (2003). Evaluation of Croatian-speaking children's speech with cochlear implants and comparison with hearing-aid users. *Journal of Multilingual Disorders*, *1*, 63–70.

Nikolopoulos, Th. P., Gibbin, K. P., & Dyar, D. (2004). Predicting speech perception outcomes following cochlear implantation using Nottingham children's implant profile (NChIP). *International Journal of Pediatric Otorhinolaryngology*, *68*, 137–141.

O'Donoghue, G. M., Nikolopoulos, T. P., Archbold, S. M., & Tait, M. (1999). Cochlear implants in young children: the relationship between speech perception and speech intelligibility. *Ear and Hearing*, *20*, 419–425.

Perkell, J., Numa, W., Vick, J., Lane, H., Balkany, T., & Gould, J. (2001). Language specific, hearing-related changes in vowel spaces, a preliminary study of English and Spanish-speaking cochlear implant users. *Ear and Hearing*, *22*, 461–470.

Pisoni, D. B. (2000). Cognitive factors and cochlear implants: some thoughts on perception, learning, and memory in speech perception. *Ear and Hearing*, *21*, 70–78.

Richter, B., Eissele, S., Laszig, R., & Lohle, E. (2002). Receptive and expressive language skills of 106 children with a minimum of 2 years' experience in hearing with a cochlear implant. *International Journal of Pediatric Otorhinolaryngology*, *64*, 111–125.

Surowiecki, V. N., Sarant, J., Maruff, P., Blamey, P. J., Busby, P. A., & Clark, G. M. (2002). Cognitive processing in children using cochlear implants: the relationship between visual memory, attention and executive functions and developing language skills. *The Annals of Otology, Rhinology and Laryngology Supplement*, *189*, 119–126.

Tait, M., Luttman, M. E., & Robinson, K. (2000). Preimplant measures of preverbal communicative behaviour as predictors of cochlear implant outcomes in children. *Ear and Hearing*, *21*, 18–24.

Tobey, E., Geers, A., & Brenner, Ch. (1996). Speech production results: speech feature acquisition. *The Volta Review*, *96*, 109–129.

Välimaa, T. T., Määttä, T. K., Löppönen, H. J., & Sorri, M. J. (2002a). Phoneme recognition and confusions with multichannel cochlear implants: vowels. *Journal of speech, language and hearing research*, *45*, 1039–1054.

Välimaa, T. T., Määttä, T. K., Löppönen, H. J., & Sorri, M. J. (2002b). Phoneme recognition and confusions with multichannel cochlear implants: consonants. *Journal of speech, language and hearing research*, *45*, 1055–1069.

Vlahović, S., & Šindija, B. (2004). The influence of potentially limiting factors on paediatric outcome following cochlear implantation. *International Journal of Pediatric Otorhinolaryngology*, *68*, 1167–1174.