SPEECH OF COCHLEAR IMPLANT PATIENTS: AN ACOUSTIC ANALYSIS OF SIBILANT PRODUCTION

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ABSTRACT

The aim of this study was to analyse sibilant production of cochlear implant (CI) patients, comparing them with normal hearing speakers (NH). Because of the inhomogeneity of cochlear implant patients, in this study they were divided into four groups, depending on whether they are prelingually or postlingually deaf speakers and the period of time between the deafening and the implantation of a cochlear implant. Each group was compared with a matched control group consisting of normal hearing speakers. Measurements were made of the first spectral moment of /s/ and /ʃ/.

The results showed significantly lower values for /s/ for all four CI groups compared to their associated control groups. /ʃ/ values were also lower for the CI speakers than for the hearing controls, but only significant for postlingually deaf speakers. The results are interpreted in terms of technical limitations of cochlear implants in higher frequency ranges and a possible adaptive strategy.

Keywords: cochlear implants, sibilants, speech production

1. INTRODUCTION

The motivation for analysing sibilant production of cochlear implant (CI) speakers is that many characteristic frequencies of the sibilant /s/ are above the audible frequency range of a cochlear implant patient. The highest audible frequencies of a cochlear implant patient normally are between 8000 – 8500Hz. Additionally the spectral resolution of a cochlear implant becomes progressively poorer at higher frequencies. This particularly affects sibilants with their characteristic higher frequency range compared, for example, to vowels.

These technical limitations affect speech production of prelingually and postlingually deaf CI patients in different ways. Prelingually deaf CI patients have never heard frequencies above about 8500Hz and are therefore used to a very restricted frequency range in the perception of /s/ and to a poor frequency resolution in the spectra of /ʃ/. In contrast, postlingually deaf CI patients were used to unaffected spectra of both sibilants during language acquisition. For them it is a challenging conversion to spectra lacking much of the characteristic information both in their own speech production and in speech of their dialogue partners. It is interesting to analyse which speaker group copes better with these unfavourable conditions.

Uchanski and Geers [9] compared 181 prelingually deaf children with cochlear implants aged 8 to 9 years with 24 normal hearing children at the same age. Among other features they examined the distance between the mean values of the first spectral moment of /s/ and /ʃ/. They found smaller distances between the mean values of the first spectral moments of /s/ and /ʃ/ produced by the children with CI compared to the normal hearing control speakers. In some cases, there was no distance at all between the two sibilants, mainly caused by substantially lower main values of the first spectral moment for /s/. These results match those of Liker et al. [3], Mildner & Liker [5] and Todd et al. [8] who also investigated sibilant production of prelingually deaf CI children.

Matthies et al. [4] analysed sibilant production of five postlingually deaf cochlear implant patients. The recordings were made twice before and six times within two years after the CI implantation. The object of the study was among other parameters the median of the first spectral moment. Two of the five subjects had values in the range of normal hearing speakers during the whole period. Two subjects differentiated hardly between /s/ and /ʃ/ before cochlear implantation, but during the following two years the distance between the median of /s/ and /ʃ/ increased. The fifth subject could not differentiate between /s/ and /ʃ/ in speech production before his CI provision. Six months later, he produced /s/ and /ʃ/ as distinct phonemes for the first time and his performance got better at the subsequent recordings.

All the mentioned studies investigate sibilant production of English or Croatian CI patients. In this study analysis is extended to German speaking CI patients. With regard to the technical limitations of a cochlear implant and the overview of available literature the present study aims to test the following hypotheses:

2. HYPOTHESES

(1) The mean values of the first spectral moment of /s/ and /ʃ/ of Cochlear implant patients are both lower than those of the normal hearing speakers.

This hypothesis is based on the assumption that cochlear implant patients shift their produced frequencies into a frequency range which is audible for them and has a better frequency resolution.

(2) The mean values of the first spectral moment of /s/ and /ʃ/ of cochlear implant patients do not differ as much as those of normal hearing speakers.

Due to the poorer frequency resolution in the higher frequency range containing the characteristic frequencies of /s/ and /ʃ/. CI patients are not able to perceptually differentiate between /s/ and /ʃ/ as well as normal hearing speakers. Therefore they do not produce as distinct sibilants as the normal hearing control subjects.

(3) Differences between groups of cochlear implant patients and corresponding control groups are greater for the alveolar sibilant /s/ than for the postalveolar sibilant /ʃ/.

This hypothesis is based on the fact that for /ʃ/, a cochlear implant provides only poorer frequency resolution. But many of the characteristic frequencies of /s/ are not audible at all for cochlear implant patients. So /s/ is more difficult to produce since there is particularly poor auditory feedback for this phoneme.

(4) There are larger differences between CI patients and normal hearing speakers in the groups with prelingually deaf CI patients compared to the groups with postlingually deaf speakers.

This is due to the fact that postlingually deaf CI patients had an unaffected language acquisition. So they learned to produce sibilants with full auditory feedback. In contrast prelingually deaf CI patients had to learn sibilant production with limited auditory feedback.

(5) The largest differences between CI patients and normal hearing speakers are shown in the group consisting of prelingually deaf CI patients who were equipped with a cochlear implant after language acquisition.

This hypothesis is based on the fact that the prelingually deaf CI patients never had unaffected hearing and that they got their cochlear implants after language acquisition so they had a very long period of time without auditory feedback. In contrast, other prelingually deaf CI patients get their cochlear implants before language acquisition and postlingually deaf speakers have unaffected auditory feedback during this critical period of time.

3. METHOD

3.1. Speakers

The tested speakers were 48 cochlear implant patients (CI) who had worn a cochlear implant for at least one year. Because of the inhomogeneity of these speakers, they were divided into four groups. The criteria for this division are as follows:

Group (1): **prelingually** deaf speakers:
equipped with cochlear implant
BEFORE language acquisition

Group (2): **prelingually** deaf speakers:
equipped with cochlear implant
AFTER language acquisition

Group (3): **postlingually** deaf speakers:
fast provision with a cochlear implant – LESS than 2 years after onset of deafness

Group (4): **postlingually** deaf speakers:
delayed provision with a cochlear implant – MORE than 2 years after onset of deafness

Additionally we recorded four groups with normal hearing (NH) speakers matched in age, sex and number of speakers.

The characteristics of the several groups are listed in Table 1.

Table 1: Properties of the four CI groups and the matched control groups.

group	number (f / m)	age CI	age NH
1	8 (3 / 5)	10.75	10.63
2	16 (13 / 3)	30.06	29.69
3	9 (8 / 1)	45	42.22
4	15 (10 / 5)	59.93	59.73

3.2. Material

The speech material consists of the German sibilants /s/ and /ʃ/. They were analysed by examining the recordings of the two words "Tasse" (/s/ *cup*) and "Tasche" (/ʃ/ *bag*) embedded in the carrier sentence "Hier steht … geschrieben" (*… is written*). The sentences were mixed with additional speech material, presented in randomised order and repeated six times each.

3.3. Parameters

Recordings were made at a sample rate of 44.1kHz. For further analysis the frequency range was restricted to 1kHz to 20kHz. The spectrum of each sound was calculated over the middle 50% of the fricative segment. Based on the method of Forrest et al. [1] the first spectral moment (mean) of the sounds /s/ and /ʃ/ was computed by first delogarithmizing the spectra and then using the function *moments* in R [7] (for further information see Harrington et al.[2]).

3.4. Statistics

Statistics were carried out with linear mixed effect analyses, separate ones for each group and sibilant (e.g. comparison between CI group 1 and control group 1 for /s/). Dependent variable is the first spectral moment, between factors are "group" (CI-group versus control group), "sex" and "age". Number of sentence repetition and subject number are random factors.

4. RESULTS

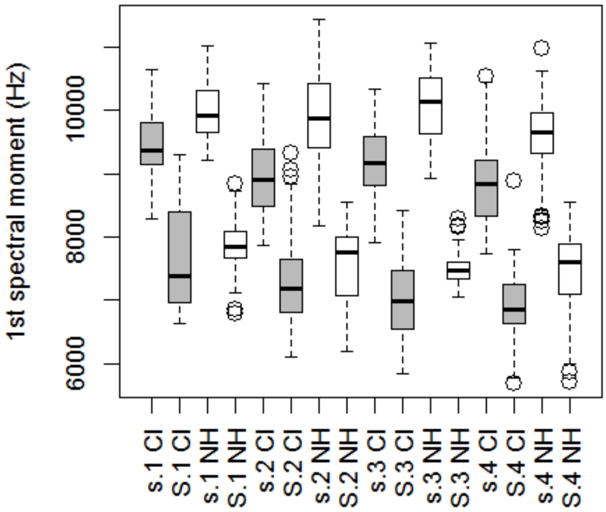
The p-values of the linear mixed effect analyses are listed in table 2. All results are additionally shown in figure 1.

For the alveolar sibilant /s/, all four CI-groups differ significantly from their control groups. For /ʃ/, there are only significant differences between the CI-groups with postlingually deafened speakers (group 3 and 4) and their control groups.

Table 2: P-values listed separately for groups (e.g. group 1 = comparison between CI group 1 and the associated control group 1) and phonemes.

phoneme	group 1	group 2	group 3	group 4
/s/ (p-value)	** 0.0004	*** 1.78e-06	** 0.0001	** 0.003
/ʃ/ (p-value)	- 0.583	- 0.186	* 0.04	** 0.002

Figure 1: Boxplots of the first spectral moments separately for the four groups of with CI patients (CI = grey /e.g. "1 CI" = prelingually deaf CI patients, equipped with a cochlear implant before language acquisition) and the four control groups with normal hearing speakers (NH = white) and the two phonemes (/s/, /S/).



Subtracting the mean of /ʃ/ from the mean of /s/ of every group results in lower values for all four CI-groups compared to their control groups (see table 3). In other words /s/ and /ʃ/ are less distinct in CI speakers. In addition, the standard deviations are higher for all the CI groups. Taken together this means that CI groups 1, 2 and 4 in particular have some speakers where the s-ʃ distinction is practically abolished.

Table 3: Mean values and standard deviations of the difference between mean of /s/ - mean of /ʃ/ listed separately for groups.

		group 1	group 2	group 3	group 4
mean	**CI**	1785.9	1656.9	2203	1984.2
	NH	2124.4	2349.4	2518.3	2097.6
standard deviation	**CI**	640.3	772.7	643.5	758.7
	NH	567.9	627.1	584.9	628.5

5. DISCUSSION

The results of this study are consistent with those of Uchanski & Geers [9], Liker et al. [3], Mildner & Liker [5] and Todd et al. [8]. For all four CI groups the frequency values of the first spectral moment for /s/ are significantly lower compared to their associated control groups. The /ʃ/ values of the CI speakers are also lower for all four CI groups compared to the associated groups consisting of normal hearing speakers. But there are only significant differences for the two groups with postlingually deaf CI patients (group 3 and 4).

These results confirm the first and third hypotheses that the mean values of the first spectral moment for /s/ and /ʃ/ are lower for the cochlear implant patients and that there are more significant differences for /s/ than for /ʃ/. The second hypothesis which says that the differences between the mean values of the first spectral moment of /s/ and /ʃ/ are smaller than those of the normal hearing is also confirmed.

The lower values of the cochlear implant patients for /s/ and /ʃ/ could be explained by the reduced auditory feedback of their own speech in the higher frequency range. If they shift the characteristic frequencies of /s/ downwards, more acoustic information is in the audible range. Downshifted frequencies for /ʃ/ are in a frequency range with a better frequency resolution. This downshifting behaviour can be seen as an adaptive strategy.

The worse differentiation between /s/ and /ʃ/ in speech production of CI patients is probably due to the fact that they are not able to perceptually distinguish between these two sibilants to the same degree as normal hearing speakers. This is probably because of the reduced frequency resolution in the higher frequency range. Additionally it is maybe an effect of the adaptive strategy, particularly the downshifted /s/. To produce the two sibilants as distinctly as normal hearing speakers, CI patients would have to produce /ʃ/ in an unduly low frequency range. Possibly there is also no straightforward articulatory strategy to shift the spectral centre of gravity down as much for /ʃ/ as for /s/. Consequently /s/ and /ʃ/ of cochlear implant patients do not differ as much as those of normal hearing speakers.

The fact that there are more significant differences between CI and control groups for /s/ than for /ʃ/ can be explained by the frequency restriction at about 8000 – 8500Hz. The characteristic frequencies of /ʃ/ are in a frequency range with poor frequency resolution. This is also the case for /s/, but these spectra are additionally cut off for CI patients.

As already discussed in the introduction, there are different conditions for prelingually und postlingually deaf CI patients in speech production, because in contrast to prelingually deaf speakers the postlingually deaf patients learn to speak with unaffected auditory feedback. But both groups have to cope with the restricted /s/ spectra. Altogether the prelingually deaf CI patients who are used to restricted spectra seem to have less problems in production of /ʃ/ than postlingually deaf CI patients. The latter speakers have learned representations of unrestricted sibilant spectra before deafness and may have therefore more difficulties to produce the same phonemes with reduced or modified auditory feedback. On the other hand in terms of the adaptive strategy the postlingually deaf CI patients actually keep greater contrast between /s/ and /ʃ/.

The results contradict our fifth and sixth hypothesis assuming greatest differences between prelingually deaf CI patients and normal hearing speakers, especially for those who got their cochlear implants after language acquisition.

6. CONCLUSION

The results of this study can be summarized as follows: CI patients and normal hearing speakers differ in sibilant production. The degree of differences between CI groups and their associated control groups depends on the onset of deafness of the CI patients (prelingually versus postlingually). Similar effects have also been shown in a study about vowel production of cochlear implant patients ([6]). The duration between onset of deafness and cochlear implant provision does not play a significant role in sibilant production.

7. ACKNOWLEDGEMENT

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