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A preliminary study of the effects of cochlear implants on the production of sibilants

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The potential influence of auditory information in the production of /s/ and /ʃ/ was explored for postlingually deafened adults with four-channel Ineraid cochlear implants. Analyses of the spectra of the sibilant sounds were compared for speech obtained prior to implant activation, after early implant use and after 6 months of use. In addition, the output of the Ineraid device (measured at each of the four electrodes) was analyzed with pre- and postactivation speech samples to explore whether the speech production changes were potentially audible to the cochlear-implant user. Results indicated that subjects who showed abnormally low or incorrect contrast between /s/ and /ʃ/ preactivation, and who received significant auditory benefit from their implants were able to increase the distinctiveness of their productions of the two speech sounds.

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INTRODUCTION

The importance of auditory information in the development of spoken language is undisputed; however, the contribution of auditory feedback in maintaining mature speech is less well understood. By investigating the speech of postlingually deafened adults both before and after they received cochlear implants, the contribution to speech production of self-hearing and listening to others can be explored. Improvements in the overall quality of the speech of cochlear implant users have been noted from the earliest investigations of these devices (cf. Bilger *et al.*, 1977). This benefit has been observed in both longitudinal studies (Tartter *et al.*, 1989; Lane *et al.*, 1991; Perkell *et al.*, 1992) and in studies of short term deprivation of auditory information (Svirsky and Tobey, 1991; Svirsky *et al.*, 1992). This approach to studying the role of auditory feedback is somewhat limited by the fact that the cochlear implant is not a perfect replacement for lost hearing, but there is no doubt that substantial auditory information is available to the successful implant user.

The effects of postlingual deafness on speech are not as dramatic as those of prelingual deafness. The overall theme of studies of the speech of adventitiously deafened adults is one of describing reduced differentiation in the contrasts between segments rather than obliteration of the phonetic segment or speech function under study. For example, in a study of seven postlingually deafened adults, Waldstein (1990) found phonetic deviations in VOT, vowels, and suprasegmentals. "While phonological distinctions were generally maintained by the majority of postlingually deafened speakers in this study, their execution was less precise." (Waldstein, 1990, p. 2111.) Lane and Webster (1991) demonstrated decreased differentiation of place of articulation in fricative

and plosive consonants. Adults with acquired deafness often maintain phonemically distinct productions of speech sounds, but if auditory feedback is critical for them to calibrate their productions, some of their articulatory patterns may eventually degrade in subtle ways.

Subjects with cochlear implants demonstrate a wide range of performance in consonant recognition. Ten Ineraid subjects tested by Tye-Murray and Tyler (1989) scored from 17%–58% correct on a 14-item consonant recognition task. Group confusion matrices available in Tye-Murray and Tyler (1989) indicate that subjects perceived 161 out of 245 (66%) of /ʃ/ items correctly and 151 out of 245 (62%) /s/ tokens correctly. Fifty-one (21%) /ʃ/ stimuli were responded to as /s/ while the incorrect responses to /s/ were predominantly /ʃ/ (16%) and /z/ (9%).

Dorman *et al.* (1990) provide consonant confusion matrices for ten subjects with the Ineraid cochlear implant categorized by overall consonant recognition performance. When the responses of three subjects who had overall scores from 65% to 81% correct on the 16-item test were combined, identification scores were 100% for /s/ and 93% correct for /ʃ/. The seven subjects with overall scores of 49%–57% correct identified /ʃ/ nearly as well (97%) as the best subjects but their score for /s/ was 26%, with errors including /b,p,θ,l/. From these studies we can expect that our subjects may perceive the sibilants with their cochlear implants and potentially use this information to affect their speech production.

A. Sibilant production by deaf speakers

Sibilant production, specifically the /s-ʃ/ distinction, represents an interesting phonetic contrast to study in cochlear-implant patients, pre- and postactivation, because the articulation required is relatively precise and complicated, there are few visual cues available, and the perception of all of the possible spectral information (up to 10 kHz) may not be available within the frequency range of the cochlear implant. To produce a good contrast between /s/ and /ʃ/, a speaker must position the tongue rather precisely and direct the air

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stream towards the lower incisors for /s/ (the /ʃ/ air stream is not as directed). The constriction is produced more anteriorly for /s/ than for /ʃ/, the cross-sectional area of the constriction is smaller for /s/, and the rate of change of the area function is greater (cf. Hoole *et al.*, 1989). These articulatory differences produce the spectral contrast that helps the listener discriminate these two speech sounds. The role of auditory feedback in maintaining this contrast may be fairly important for without it the critical aspects of the articulation may be less distinct, leading to less differentiated acoustic results. Lane and Webster (1991) compared the speech of three profoundly deaf subjects who had become deaf after acquiring speech and language with that of matched normal-hearing subjects. Among other phonemes, they examined production of /s/ and /ʃ/. They used the spectral midpoint of the frequency distribution of the sibilant sound after FFT (cf. Jassem, 1979) and found that the deaf subjects did not produce as differentiated /s/ and /ʃ/ as the control subjects. Specifically, the midpoints of the /ʃ/ spectra were significantly higher in frequency (and therefore closer to the midpoints of the /s/ spectra) for the deaf subjects than for the normal hearing subjects.

Economou *et al.* (1992) report results from a subject who had been using a single-channel cochlear prosthesis and then was without an implant for 18 days before receiving a multichannel device (Nucleus-22). They compared spectrograms obtained when the subject was using the single-channel implant to those obtained 1 day and 18 days after no implant was available and 1 day, 6 months and 1 year after a multichannel device had been in use by their subject. Economou *et al.* found that when the subject was not receiving auditory input, the spectrum for /s/ became inappropriately broad, covering most of the 1–5 kHz range. The frequency distribution for /s/ returned to a narrower high-frequency range when the subject received the multichannel implant.

B. Sibilant spectral analysis

There is a wide range of variability in the production of a given speech segment by normal-hearing speakers even when the surrounding phonetic environment is similar. Boothroyd and Medwetsky (1992) systematically investigated the effect of phonetic context, intersubject differences and gender on the production of /s/. They identified the lowest-frequency prominent peak in the power spectra (which had to be within 10 dB of the largest overall peak) for five female and five male speakers. With a following /a/, the frequency of the peak for the female speakers ranged from 5.6 to 8.9 kHz, which did not overlap the results for the male speakers whose peaks ranged from 3.4 to 5.3 kHz. This range of differences among speakers is one of the issues which must be considered in devising methods to investigate the benefit of information from a cochlear implant on sibilant production.

Forrest *et al.* (1988) classified word-initial voiceless obstruents using a statistical analysis. By treating the spectral data (resulting from FFT of the speech) as a random probability distribution, they calculated the mean, variance, skewness, and kurtosis for the distribution. This quantitative analysis provides us with an approach to objectively describe

the initial contrast between the phonetic segments and any longitudinal changes for our subjects.

Given the intersubject variability of normal speech and the diverse effects of deafening on speakers, it is most appropriate for each cochlear-implant subject to serve as his/her own control longitudinally. We will examine how the speaker regulates the /s/ and /ʃ/ contrast rather than to study a specific location of either of these phonemes in the wide range of acceptability. The goal of the current study, then, is to analyze various aspects of sibilant spectra to determine if auditory feedback in the form of input from a cochlear implant significantly affects the contrast between /s/ and /ʃ/.

I. METHODS AND PROCEDURES

A. Subjects

Subjects included two male and three female users¹ of the Ineraid cochlear implant (Richards Medical Co.). Subject FA had a congenital monaural impairment and had used a hearing aid until she became profoundly deaf bilaterally at the age of 33. Subject FB became profoundly deaf at age 41; she had normal hearing until she was 21 and was a hearing aid user in the 20 years of progressive hearing loss. Subject FC had a severe bilateral hearing loss from early childhood and wore hearing aids until she was 47 when they began to cause vestibular problems for her. Subject MB became deaf after meningitis at age 4 and used hearing aids. The other male subject, MC had a progressive bilateral hearing loss which started at approximately age 10 and had consistently used a hearing aid. Thus all cochlear implant subjects were postlingually deafened and relied on an oral/aural mode of communication in their daily activities. Four of the five implant subjects receive significant perceptual benefit from their devices and wear them regularly. One of the male subjects (MB) received little benefit in speech perception and gradually decreased his use of the processor until he was no longer using it after these recordings were made.

The external sound processor (Eddington, 1983) of the Ineraid cochlear implant filters the incoming speech signal into four frequency bands and delivers the outputs to four monopolar intracochlear electrodes (with a common return electrode). Filter crossover points are at approximately 700, 1400, and 2300 Hz and the center frequencies for the four channels are 500, 1000, 2000, and 3400 Hz. The electrodes were inserted into the scala tympani through the round window and positioned successfully in all subjects with the first electrode placed approximately 22 mm from the round window. Channel-specific gains were set individually for each subject at the time of the speech processor activation. [See Eddington (1983) or Youngblood and Robinson (1988) for further information.]

B. Data collection

Two baseline recording sessions separated by 1–10 weeks were made for each of the subjects prior to them receiving their cochlear implants, followed by recordings made at approximately 0, 4, 12, 26, 52, and 104 weeks postactivation. Subjects did not receive speech therapy or auditory

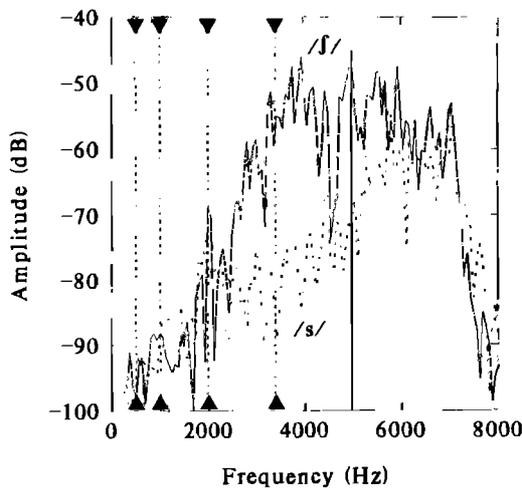


FIG. 1. Frequency distributions of /s/ (dotted line) and /ʃ/ (solid line) produced by a normal-hearing female subject. Filled triangles are placed at the center frequencies of the Ineraid speech processor channels. The solid line at 5500 Hz represents the upper bound of our analysis.

training during this research period except for subject FC who began speech therapy a month prior to the recording at 104 weeks.

The subject was seated in a comfortable chair in a sound-treated room. A small electret microphone was placed at a distance of 20 cm from the subject's mouth by attaching it to a flexible arm affixed to the back of the chair. The speech materials were projected on a screen within easy viewing distance of the subject. Subjects repeated the phrase "It's a /sɒd/ again" or "It's a /ʃɒd/ again" three times during an experimental session; these tokens were embedded in a corpus which contained a large variety of speech materials.

This experiment is part of a larger project in which a number of physiological measures are studied along with the acoustic signal. To make the required multichannel recordings we use a PCM recorder with a 12-kHz/channel sampling rate and a 5.5-kHz low-pass antialiasing filter. We assumed that although the 5.5 kHz would limit the high-frequency information for the fricatives, it would still be possible to determine implant-related changes in /s/ and /ʃ/ on the basis of frequency information below 5.5 kHz. Considering that the frequency response of the cochlear implant is limited (i.e., the highest center frequency of the Ineraid is 3.4 kHz) compared to the frequency range of the normal peripheral auditory system, our 5.5 kHz upper bound comfortably covers the bandwidth of the information our subjects have available. Digitization, signal processing and data analysis were completed with procedures written in the MITSYN software family (Henke, 1989; Perkell *et al.*, 1991) running on a Digital Equipment Corporation (DEC) engineering workstation.

C. Spectral analysis of the fricatives

The initial goal of the analysis was to quantify the difference between the /s/ and /ʃ/ spectra. A comparison of the two sibilants, as produced by a normal-hearing female speaker and then digitized at 16 kHz, is found in Fig. 1 with the center frequencies of the four channels of the Ineraid

processor indicated by filled triangles. The spectrum of the /s/ is traced with a dotted line and is characterized by a fairly defined peak between 5 and 7 kHz. The spectral shape for the /ʃ/ is more symmetric around its midpoint at 5 kHz and has a broad plateau rather than a peak.

In addition to the acoustic analyses of /s/ and /ʃ/, we also examined the output of the Ineraid speech processor for the two sounds. Differences between the two sibilants are found in electrodes 3 and 4 with a much greater amplitude difference between electrodes 3 and 4 for /ʃ/ than /s/. The information available at electrodes 3 and 4 therefore is potentially useful for distinguishing /s/ from /ʃ/ and the comparison between amplitudes at electrodes 3 and 4 would facilitate their discrimination.

We used the Forrest *et al.* approach to quantify the possible changes in both the shape (i.e., skewness) and center (i.e., median) of the sibilant spectra that could accompany the use of the cochlear implant. The center portion of the sibilant waveform was identified by the experimenter and a 512 point FFT was calculated. The power spectrum $p(k)$ was calculated by summing the squared real and imaginary components of the Fourier spectrum thereby obtaining the $A(k)$ coefficients and normalizing them as in Eq. (1):

$$p(k) = \frac{A(k)}{A(1) + \dots + A(256)}. \quad (1)$$

The normalized power spectrum was treated as a frequency distribution and its mean, variance, skewness and kurtosis were determined as shown in Eqs. (2)–(5). For the purpose of this discussion, we use the term symmetry in place of skewness for the third moment and peakedness to replace kurtosis for the fourth moment:

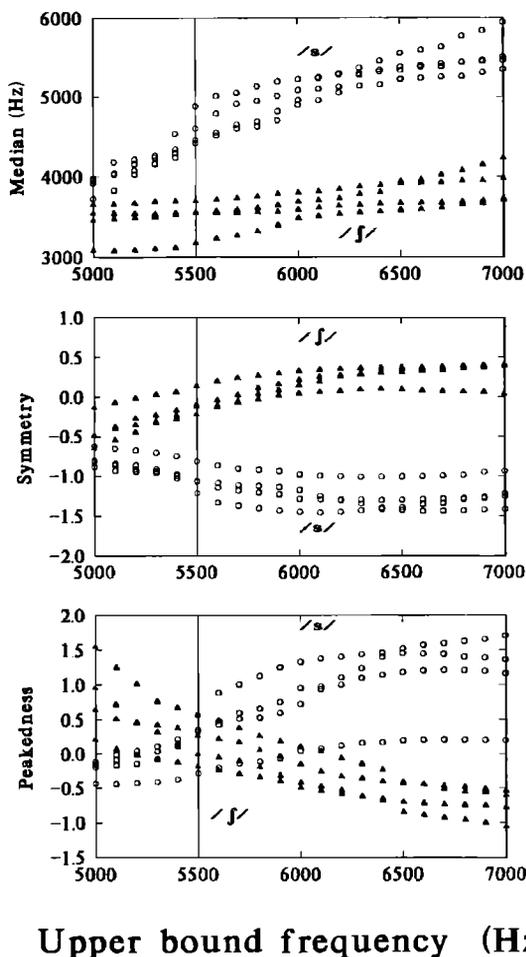
$$\text{mean} \quad L_1 = f_1 p(1) + \dots + f_{256} p(256), \quad (2)$$

$$\text{variance} \quad L_2 = (f_1 - L_1)^2 p(1) + \dots + (f_{256} - L_1)^2 p(256), \quad (3)$$

$$\text{symmetry} \quad L_3 = (f_1 - L_1)^3 p(1) + \dots + (f_{256} - L_1)^3 p(256), \quad (4)$$

$$\text{peakedness} \quad L_4 = (f_1 - L_1)^4 p(1) + \dots + (f_{256} - L_1)^4 p(256). \quad (5)$$

In addition, we calculated the median by cumulating the normalized power spectrum above 1000 Hz and identifying the frequency at which the 50% point occurred. Calculation of the median allows us to compare our results with those of Lane and Webster (1991) who used this metric but were able to analyze their spectral data up to 10 kHz. In an initial test of these metrics, a normal-hearing female speaker produced (with an effort to provide some intertoken differences) four /s/ and four /ʃ/ tokens. Four tokens each of /s/ and /ʃ/ from the normal-hearing female speaker whose sibilant spectra are illustrated in Fig. 1 were digitized at 16k samples per second and analyzed. The averaged values for /s/ median was 6.44 kHz (with a standard deviation of 0.09) and for /ʃ/ was 4.59 kHz (with a standard deviation of 0.16). The means (and standard deviations) of the symmetry measure were -1.90



Upper bound frequency (Hz)

FIG. 2. Upper bound effect on the median, symmetry, and peakedness for /s/ (open circles) and /ʃ/ (filled triangles). The solid line at 5.5 kHz denotes the upper frequency limit for the current study.

(0.13) for /s/ and -0.04 (0.10) for /ʃ/. Clearly, the median and symmetry measures are useful in describing the spectral distributions of /s/ and /ʃ/ (Fig. 1).

To validate our assumption about the usefulness of the 5.5-kHz bandlimited recordings, we explored the effect of the upper bound of the frequency distribution. The same eight productions from the normal-hearing speaker (digitized at 16 kHz) were analyzed with a series of upper frequency filter cutoffs ranging from 8.0 kHz down to 5.0 kHz. The primary purpose of this analysis was to see if the spectral differences between /s/ and /ʃ/ would still be identifiable with an upper frequency bound of 5.5 kHz. Results for the median, symmetry, and peakedness measures are found in the top, middle, and bottom panels of Fig. 2, respectively. Calculations for each of the productions are displayed with a solid vertical line located at 5.5 kHz which is the upper bound for analyzing the cochlear-implant subjects' speech in the current recording setup. There is a reasonable separation for /ʃ/ and /s/ using the median and symmetry parameters (Fig. 2, top and middle panel) with the 5.5 kHz upper bound, verifying our assumption that we can determine differences between these two phonemes on the basis of frequency information below 5.5 kHz.

For the peakedness calculation (Fig. 2 bottom panel) we

found that an upper bound of at least 6.0 kHz is needed before a reasonable distinction between /s/ and /ʃ/ can be seen. The results for spectral means were similar to those for the median so we have chosen to concentrate on symmetry and median as the descriptors of the sibilant spectra.

II. RESULTS

Sibilant productions of the cochlear-implant subjects with a (5.5 kHz upper bound) were analyzed, results for the median and symmetry measures from the five subjects are found in Fig. 3. Speech samples obtained prior to the cochlear implant are designated *pre*, data collected within several months of processor activation are labeled *post*, and data obtained after the subjects had been using their implants for 6 months or more are designated with *six*. The open circles represent data for /s/ tokens and the filled triangles are used for /ʃ/.

In normal-hearing speakers /s/ should have higher median values and lower symmetry values than /ʃ/ (cf. Figs. 1 and 2). For subject FA, (first row of Fig. 3) preimplant median and symmetry results shows a significant contrast between the sibilants and she maintains these patterns with the activation of the cochlear implant. Her productions are very similar to results obtained from the normal-hearing female we used to test our analysis technique. Subject MB (fourth row) also maintains a separation between the two speech sounds but it is not as strong a contrast as subject FA's. Subjects FB (second row) and MC (last row) improve their /s-/ʃ/ contrast primarily by decreasing the symmetry of /s/ in their data after 6 months of cochlear implant use. The subject with the poorest sibilant contrast in preimplant speech, FC, produces more appropriate spectra only after using the prosthesis for 6 months. These graphical observations were tested with repeated measures ANOVAs for each subject with cochlear implant use (pre-, post-, or >6 months postimplant) and the sibilant type (/s/ or /ʃ/) as trials factors. Table I contains the proportion of variance accounted for, η^2 (Marascuilo and Serlin, 1988) associated with significant ($p < 0.05$) F ratios for the two main effects, cochlear implant use (pre, post, and more than six months) and sibilant category, and their interaction.

Sibilant category accounts for most of the variance in both the median and symmetry measures for subjects FA and MB. Both of these subjects had distinct contrasts between /s/ and /ʃ/ with respect to spectral shape and location prior to receiving their cochlear implants and have maintained patterns that are similar to those we see with the normal-hearing subject. The main effect of sibilant type is larger for FA than MB and the contrast between FA's two sibilant categories is also greater as seen in Fig. 3.

Subjects FB and MC also had a similar pattern of results to each other in the ANOVAs. In addition to the main effect of sibilant category seen with subjects FA and MB, they also had significant main effects for implant status with both the median and symmetry measures. For subject MC, the main effect for implant status results from the steady rise in the median frequency of /s/ in the postprocessor conditions while for subject FB, median frequencies for both /s/ and /ʃ/ rise in those conditions (cf. Fig. 3). For both subjects, the

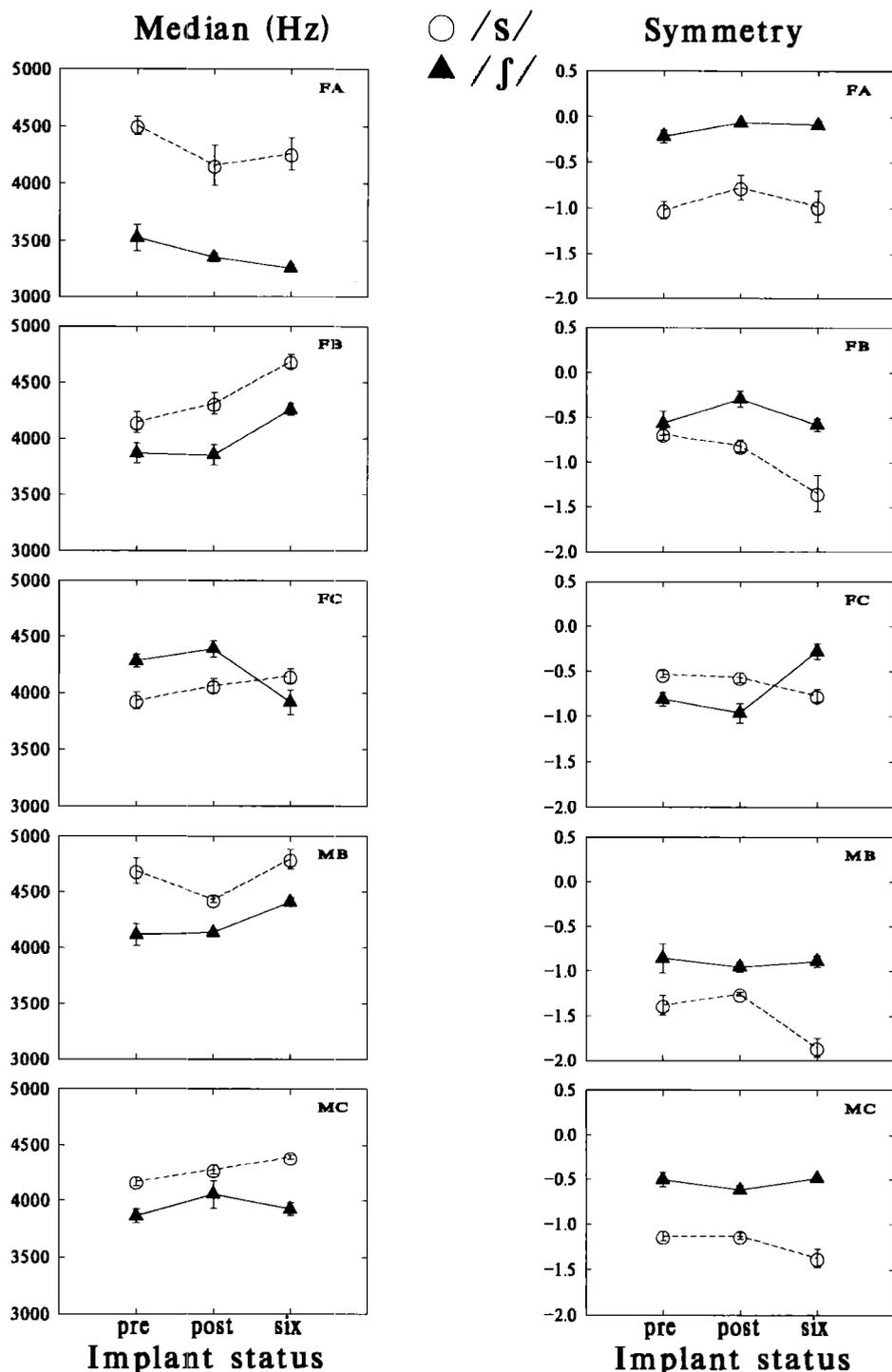


FIG. 3. Spectral medians (left) and symmetry (right) for /s/ (open circles) and /ʃ/ (filled triangles) for five cochlear-implant subjects. The error bar corresponds to the \pm one standard error of the mean.

small main effects for implant use are due primarily to the drop in symmetry of /s/ for data taken after six months.

An interaction effect between implant and sibilant category for the symmetry results, which accounts for 12.5% of the total variance in this analysis, was found in subject FB's data. The interaction effect is easily observable for subject FB in Fig. 3 where /s/ has become less symmetric as the implant status has changed. That is, when the ANOVA interaction effect is not statistically reliable, the direction and size of the effect of the implant is similar for the two sibilant

categories. In FB's symmetry results, the two sibilants are diverting over the course of the experiment, which results in an improved contrast between them.

The findings for subject FC are very different from the other four subjects. The overall effect for sibilant category is not statistically reliable with the symmetry measure because this subject did not differentiate the sibilants until after she had been using the implant for 6 months. Both of the interaction effects are significant, and by noting the direction of this interaction in Fig. 3, we can see that the subject is ef-

TABLE I. Proportion of variance accounted for with the repeated measures ANOVAs where the F ratios were significant ($P < 0.05$).

Subject	FA	FB	FC	MB	MC
Median					
Sibilant	0.75	0.34	0.11	0.58	0.48
Implant use		0.39	0.12		0.18
Sibilant X implant use			0.36		
Symmetry					
Sibilant	0.73	0.30		0.57	0.81
Implant use		0.19	0.14		0.04
Sibilant X implant use		0.12	0.54		

fectively improving the contrast between the sibilants in both the spectral shape as captured by the symmetry measure and the spectral location as measured by the median. Data obtained in the last two sessions (at 52 weeks and 104 weeks) was similar, suggesting that the month of speech therapy had not affected our measures of sibilant production.

A. Ineraid output voltages

All of the cochlear implant subjects² were able to identify /s/ in a 12-item auditory-only, consonant confusion task [cf. Rabinowitz *et al.* (1992) for details]. To further explore whether production changes could in principle be attributed to implant use, sibilant productions were analyzed as follows. Digitized speech samples from subject FB were played into an Ineraid implant to see if the changes the subject had made in the /s/ productions could be observed in the output electrode voltages. It is important to note that these observations are independent of any specific channel gains set for an individual implant user. Speech processors of different subjects have different gains in each channel but the amplitude difference in a particular channel between productions of /s/ and /ʃ/ will not be affected. Similarly if the cue used by the subject with an Ineraid device for this discrimination is the amplitude ratios in channels 3 and 4, the differences in amplitude ratios for /s/ and /ʃ/ are independent of channel gains.

The results are found in Fig. 4 with open circles for the electrode output of preimplant productions of /s/ and filled circles for postactivation (>6 months) productions of /s/. Subject FB produced /s/ with relatively more high-frequency energy (electrodes 3 and 4) postimplantation. The results in Fig. 4 are consistent with the shifts in the median and symmetry of the /s/ seen in Fig. 3 for FB. Using the amplitude of electrode 1 as a reference, FB raised the amplitude in electrode 3 by 4.45 dB and the amplitude in electrode 4 by 3.7 dB. These differences in amplitudes are large compared to the minimum change in electrical amplitude that is discriminable. For example, Eddington *et al.* (1978) found a 0.35-dB intensity difference limen with a user of the Ineraid device. Thus subject FB is likely to be able to perceive the difference between her pre- and postimplant productions of /s/. This observation is by no means a definitive test of whether the subjects were using auditory information to modify their speech patterns; however, if there had been no difference for the electrode outputs, an auditory explanation for our results would be untenable.

III. DISCUSSION

Subjects with the Ineraid device in the Dorman *et al.* (1990) study were able to identify /s/ and /ʃ/ successfully, presumably because the auditory information provided to electrodes 3 and 4 is substantially different for the two speech sounds. Thus, our subjects had auditory information available from their implants to improve or maintain their speech. While the information available from a cochlear implant may help the speaker perceive correct models of speech and monitor his/her own speech, subjects will differ widely in their ability to use this information. For example, subjects FB and MC both showed a steady rise in /s/ median frequency, and a drop in /s/ symmetry throughout the course of the experiment, (thereby increasing the contrast between /s/ and /ʃ/) while subject FC showed little improvement in the first few months of cochlear implant use.

Not all of the subjects had a diminished /s-ʃ/ contrast preimplant. Two subjects managed the /s-ʃ/ contrast well without auditory feedback (FA and MB) and therefore did not need to improve their sibilant production. In the case of subject MB, the preimplant phonetic contrast in his speech for /s/ and /ʃ/ was adequate and he appears to be maintaining this contrast. The same was true of subject FA who had excellent contrast between /s/ and /ʃ/ preimplant (entirely comparable to the normal-hearing subject we used to test our analysis techniques) and as might be expected did

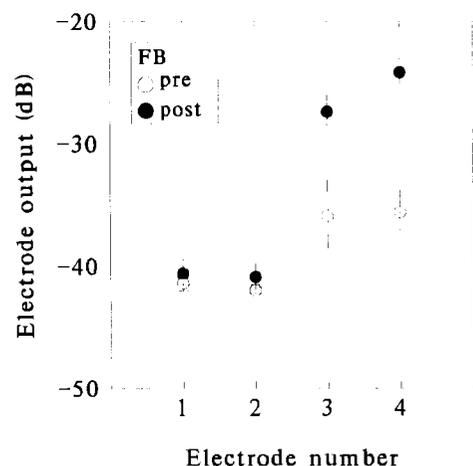


FIG. 4. Electrode amplitudes from the Ineraid implant for pre- (open circles) and postimplant (filled circles) productions of /s/ by FB as input to the speech processor.

not alter these speech segments when auditory information was provided by the implant.

The current study was concerned with relatively static aspects of the sibilants /s/ and /ʃ/, as the spectra were determined in the center of the continuant. There are dynamic characteristics of these speech sounds that may also improve longitudinally as the subjects make use of the auditory information available from their cochlear implants. Directions for further research with this subject group include investigating any longitudinal trends in the relation between the sibilant and its following vowel with respect to coarticulation and characteristics of airflow management.

IV. SUMMARY AND CONCLUSIONS

Three of five subjects (FB,FC,MC) with cochlear implants showed improvement in their sibilant production after processor activation. The two subjects (FB,MC) who had a poor contrast prior to activation, were able to improve the phonetic distinctiveness between /s/ and /ʃ/ significantly. The subject who did not have distinct categories for these two speech sounds (FC) was able to develop the appropriate contrasts in spectral shape and location but only after 6 months of implant use. Subjects FA and MB demonstrated good contrast between /s/ and /ʃ/ prior to obtaining a cochlear implant and have been able to maintain the contrast between these two speech sounds.

These results are consistent with the findings of Lane and Webster (1991) that postlingually deafened adults may demonstrate a diminished contrast between the medians of /s/ and /ʃ/ frequency distributions. The current study extends their work to include the shape of the sibilant spectrum and demonstrates that the contrast can be improved when the subject receives a cochlear implant. Perceptual testing (cf. Dorman *et al.*, 1990) supports the idea that many cochlear implant subjects perceive the /s-/ʃ/ distinction in normal speech, and data we obtained with the Ineraid electrode outputs indicate that they may also be able to use this information to monitor and improve their own speech. These results suggest that for the subjects who showed diminished contrast prior to implant, the restoration of some auditory feedback facilitated the accurate production of these two speech sounds so that they became more distinct.

ACKNOWLEDGMENTS

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¹Subjects are identified to be consistent with Perkell *et al.* (1992) which included subjects FA, MA, and MB. The present study included two new

subjects FC and MC who were not described in Perkell *et al.*, 1992. Subject MA from that study did not produce a fricative when asked to read /ʃud/ and his data were not analyzed for this study. In other publications from the Massachusetts Eye and Ear Infirmary subjects were identified by a different code FA=S09, FB=S15, FC=S23, MB=S11, MC=S19.

²Subject MB did not receive as extensive perceptual testing as the other subjects because of his generally poor performance with the implant. At 56 weeks postactivation, he scored 38% (chance=25%) on the initial-consonant subset of the MAC battery.

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