Speech Production Changes with the Use of a Multichannel Cochlear Implant in a Postlingually Hearing Impaired Adult

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ABSTRACT

Profoundly deaf cochlear implant users provide an interesting population in which to assess the role of distorted auditory feedback in speech, since their electrically stimulated hearing is significantly different from normal hearing. The aim of the study was to evaluate, by means of spectrographic and listener analyses, the speech production changes in a postlingually deafened adult with the use of a multichannel cochlear implant over time, compared to that of hearing aids as well as no-amplification. The results indicated significant improvements in the use of suprasegmental speech features as well in the production of specific segmental features of speech.

OPSOMMING

Uitermatige dowe pasiënte met kogleêre inplantings vorm 'n interessante populasie waarby die invloed van versteurde ouditiewe terugvoer op spraak ondersoek kan word, aangesien elektries-gestimuleerde gehoor betekenisvol verskil van normale gehoor. Die doel van die studie was 'n ondersoek na die invloed van 'n multikanaal kogleêre inplanting oor 'n verloop van tyd, in vergelyking met geen ouditiewe versterking en versterking dmv gehoorapparate op spraakproduksie van 'n postlinguale dowe volwássene. 'n Vergelykende spektrografiese en luisteraaranalise is uitgevoer. Die resultate het betekenisvolle verbeteringe getoon in die suprasegmentele, sowel as spesifieke segmentele eienskappe van spraak.

INTRODUCTION

Research on the benefits of cochlear implants have in the past focused primarily on the speech perception of the postlingually deafened implant user (Dowell, Brown, Seligman & Clark, 1985; Dowell, Seligman, Blamey & Clark, 1987; Eddington, 1983; Cohen, Waltzman & Shapiro, 1985 and Schindler, Kessler, Rebscher, Yanda & Jackler, 1986). Improvements in environmental sound recognition as well as improvements in auditory sensitivity (Thielemeir, Eisenberg & Brimacombe, 1982; Tyler, Gantz, McCabe, Lowder, Otto & Preece, 1985) have also been widely documented. An increasing number of researchers have begun to place emphasis on the speech production characteristics of postlingually deafened implant wearers, (Iler-Kirk & Edgerton, 1983; Leder, Spitzer, Milner, Flevaris-Phillips, Richardson & Kirchner, 1986; Tartter, Chute & Hellman, 1989; Waldstein, 1990; Lane & Webster, 1991; Economou, Tartter, Chute & Hellman, 1992; Perkell, Lane, Svirsky & Webster, 1992; Svirsky, Lane, Perkell & Wosniak, 1992). The lack of research directed at the speech production changes could be due to the fact that a postlingually acquired deafness does not necessarily lead to problems of speech degeneration (Ling, 1976). Studies designed to investigate the speech characteristics of postlingually deaf subjects have, however, found that longterm total auditory deprivation in hearing adults resulted in eventual deterioration into flat, unmodulated and dysprosodic voice, (Cowie, Douglas-Cowie & Kerr, 1982). Waldstein (1990) investigated some effects of postlingual deafness on speech by exploring selected properties of consonants, vowels and suprasegmentals in the speech of seven totally, postlingually deafened individuals. Their results demonstrated that postlingual deafness affects the production of all the classes of speech sounds. Re-introduction of "auditory input" with the electrical stimulation of the auditory nerve should result in changes in speech production. These changes in speech production are primarily reliant on the type of information derived from stimulation and finally the implant listener's articulatory adaptation to prolonged profound deafness, (Perkell et al., 1992).

The most common changes in speech production with the use of multichannel cochlear implants can be described in terms of suprasegmental and segmental changes, although previous studies have indicated that the suprasegmental features are affected the most due to the presence of a profound hearing loss, (Leder et al., 1986). Waldstein, (1990) indicated that the results of his study do not support the hypothesis that the suprasegmental properties of speech show the greatest effects of a loss of auditory feedback, while the segmental properties remain relatively unaffected. "Rather, auditory feedback appears to be implicated in monitoring and maintaining phonetic precision in all classes of speech sounds." Waldstein, (1990:211).

Various studies investigating the effects of multichannel cochlear implants on speech production have indicated that significant changes in speech production can occur with the use of a multichannel implant. Lane & Webster, (1991) have reviewed some of the studies investigating the speech of postlingually deafened speakers including several studies on the effects of cochlear implants. They conclude that the majority of studies implicate a role for audition in regulating, directly or indirectly, several speech properties including voice quality, voice aspiration, vocal duration, pitch, intonation, stress, tempo, nasality and frication and plosive articulation, (Iler-Kirk & Edgerton 1983; Leder et al., 1986; Tartter et al., 1989; Economou et al., 1992; Perkell et al., 1992).

METHOD

AIMS

The aim of the present study was to evaluate the speech production changes brought about by the use of a multichannel cochlear implant over time, in an adult with a profound postlingual sensorineural hearing loss. The subject's speech production skills were evaluated pre- and post-operatively by means of spectrographic and listener analyses. These evaluations included:

- the spectrographic evaluation of the *suprasegmental* features of speech, in terms of *sentence duration, fundamental frequency variations* and *word stress (amplification).*
- the spectrographic evaluation of the *segmental* features of speech, namely vowels and consonants. The vowels were evaluated in terms of *vowel length* and the *formant relationships between F1 and F2.* The consonants were evaluated in terms of the *spectral noise band frequencies for fricatives,* the *spectral frequency ranges for the plosive sections of the stop sounds* and the *relative amplitude peaks* of both the fricatives and plosives.
- the listener's analysis of speech production was evaluated in terms of *pitch variation, and vocal and pausal duration.*
- the results of the speech production changes with the multichannel cochlear implant over time were compared to the subject's speech production without any amplification and with binaural hearing aids.

RESEARCH METHODOLOGY

A single-case research study using a time series experimental design was used in order to evaluate the speech production changes with the use of a multichannel cochlear implant in an adult with a postlingual sensorineural hearing loss. The data was obtained by performing evaluations in the following phases:

Pre-implant:	No-amplification (NA); hearing aid (HA)
Post-implant:	0-months (CI-0), 3-months (CI-3) and 6-months (CI-6) cochlear implant

SUBJECT

The subject (MC) lost his hearing due to meningitis at 19 years of age. He was implanted five years later. His pre-implant audiograms indicated a bilaterally total sensorineural hearing loss with minimal benefit from binaural hearing aids as well as a vibrotactile device. His right ear was implanted on 31 October 1991 with the Cochlear 22-channel implant. All electrodes were easily inserted. The electrodes were programmed in the Bipolar + 1 mode using the MPEAK coding strategy. The subject (MC) was an Afrikaans speaker using a non-standard dialect.

IMPLANT AND SPEECH PROCESSOR

The cochlear implant used in the present study is known as the Mini-System 22 comprising 22 pure platinum bands supported on a flexible silicone rubber carrier. The speech processor utilized is referred to as the MSP (Mini Speech Processor). The MPEAK coding strategy extracts and codes F1 and F2, where the F1 is represented by the dominant spectral peak in the range from approximately 300-1000Hz and F2 between 800-4000Hz. The estimate of F1 from the acoustic signal controls the selection of an apical electrode pair, while the estimate of F2 controls the selection of a basal electrode pair. The spectral energy in the regions of 2000-2800Hz, 2800-4000Hz and above 4000Hz are presented to three basally located electrodes. The fundamental or voicing frequency determines the pulse rate of the stimulation and the amplitude of the acoustic signal determines the stimulus intensity, (Cochlear, 1989).

HEARING AIDS

The two Phonak PPC-L-4 hearing aids were utilized in the pre-implant evaluation condition. The maximum output of the hearing aids is 142 dB SSPL with a frequency range of 140 - 4900 Hz. The subject used the hearing aid on volume 2,5 with the following settings: LC - 1, HC - 5, G - 6 and SSPL - 6. The subject also wore new standard acrylic ear moulds.

STIMULI AND EQUIPMENT

The data for the evaluation of the subject's speech production skills were determined objectively and subjectively by means of spectrographic and listener analyses respectively. For the *spectrographic analysis* of the *suprasegmental features* of speech, seven sentences varying in length and including the various typical prosodic features of statements, questions and commands, were selected to be spectrographically analyzed. For the *spectrographic analysis* of the *segmental features*, eight isolated single vowels; / i /, / a /, = / y /, / œ /, / u /, / ə /, / ɔ / & / ɛ / in CVC combinations were selected to be analyzed. The vowels selected were the most common vowels utilized in Afrikaans where the transition to diphtongs does not take place. The consonants selected were those consonants which are either ommitted or distorted in the presence of a profound hearing loss (Nickerson, 1975). The plosives, / t /, / k /, / p / and the fricatives / s / and / x / were used in the final position and / s / and / f / were used in the initial position of the word. These consonants were analyzed within the context of two different words and preceded or followed by different vowels. For the listener analysis, the subject was required to read a paragraph in which the length, language, content and complexity was appropriate for the purpose of the evaluation as well as the subject's reading skills.

The specified material was read into a Dynamic MO2 NCC microphone (15cm from the microphone) in an IAC soundproof and sound reverberation free unit. The recordings were made on a Nachamitchi, model 682 2X Direct Head Casette Deck. The speaker's distance from the microphone as well as the input attenuation were kept constant throughout all the recordings. Spectrographic analyses were conducted using the KAY DSP Sonagraph, Model 5500. The analysed data was graphically displayed on a NEC/Multisync colour monitor.

PROCEDURE

Recording of data

Recordings of all the stimulus words and sentences were made without any amplification of the signal in the pre-implant condition, with binaural hearing aids in the pre-implant condition, the following day after switch-on i.e., 0- months; 3-months and 6-months post-implant.

Spectrographic analysis

For the analysis of the suprasegmental features, a combination analysis setup of the sonagraph, whereby the waveform, amplitude and pitch trace of the sentences were displayed, was used for the measurements. The *sentence duration* was measured by applying time cursors on the speech wave display. *Pitch variation* was determined by using the frequency cursor readings on the computed pitch curves at the highest and lowest peaks in the pitch trace. *Word stress* or amplification was measured by the time cursors at the highest peak of computed amplitude curves.

The analysis of *segmental features* of specific speech sounds focused on the *duration* and *formant frequencies* of vowels and the *spectral characteristics* of the fricatives and the plosive energy of stop consonants. The vowels were analyzed up to 4000Hz and the consonants up to 8000Hz. A combination display of a wideband spectrogram in conjunction with a narrowband amplitude spectrum of the computed spectral energy between two time cursors was used. Time cursors were used in order to determine the length of the vowel. For the measurements of the formant frequencies, a stable middle portion of each vowel was selected in order to exclude the transitions to the consonants. Frequency cursors, in conjunction with the time cursors were utilized in order to determine the formant frequencies.

The consonants were analyzed in terms of the *spectral noise band frequencies* for the fricatives (i.e., minimum and maximum frequencies of the fricatives), the *spectral frequency range* for the plosive sections of the stop sound (i.e., minimum and maximum frequencies of the plosive sections of the stop sounds) and the relative *amplitude peaks* of the fricatives and plosives. Time and frequency cursors were used to determine the frequency boundaries as well as the relative amplitude peaks.

Listener analysis

For the listener's evaluation of the subject's speech production, a rating scale for listener's evaluation of *pitch variation* and *vocal and pausal duration* was used, (Coles, 1990). The recordings were presented to four trained listeners via Tandberg Educational headphones in a language laboratory by means of a Tandberg Educational IS10 cassette player. The listeners were asked to evaluate pitch variation, vocal duration and pausal duration by means of a five point rating scale (Appendix A).

RESULTS

RESULTS OF THE SPEECH PRODUCTION EVALUATION USING SPECTROGRAPHIC ANALYSIS.

It is important to note that there were no marked abnormal characteristics pertaining to the subject's suprasegmental and segmental features as found in some postlingually deafened adults. Spectrographic analyses were executed in order to detect any degeneration of speech features which had possibly occurred during the period of profound deafness as well as any changes in speech production brought about by the use of the cochlear implant.

Suprasegmental features

The results of sentence duration across various auditory input situations are presented in Table 1.

When analyzed, the majority of the sentences showed an increase in *sentence duration* at the six month cochlear implant level, as opposed to the no-amplification and hearing aid conditions. The increases in sentence duration occurred at either the cochlear implant 0-month or 3-month situation, with a highest mean duration for the seven sentences at 0-months. A qualitative analysis of the individual sentences does, however, give logical explanations for these results. The interpretation and explanation of the above findings will be given in the discussion of results.

As can be seen in Table 2, the highest relative amplitude peaks for stressed words showed a small, however, consistent increase in the amplitude range with the use of the cochlear implant, with the values ranging from 33,1dB, 37,4dB and 37dB during the 0-, 3- and 6-month cochlear implant intervals, compared to 31,7dB and 34dB obtained during the no-amplification and hearing aid conditions respectively. The values for all sentences obtained during the 3-month interval showed an increase in amplitude peaks when compared to the 0-month interval. During the 6-month interval, however, there was a slight decrease in amplitude peaks for sentences two, four and six when compared to the 3-month cochlear implant interval. These values compared to the 0-month interval did, however, show an increase in amplitude range.

The results of the *fundamental frequency (F0) variations,* including the minimum and maximum F0 values as well as the differences in F0 across the various auditory input situations, are presented in Table 3.

As can be seen in Table 3, the mean difference in fundamental frequency variations for the no-amplification (49,7Hz) and hearing aid (48,7Hz) situations did not differ significantly from one another. Surprisingly, the results for the 0-month cochlear implant interval showed a decrease in F0 variation (44,4Hz). A significant increase in the mean F0 variation occurred at the 3-month interval (110,7Hz), indicating a possible over compensation in the use of varying F0. The results obtained at the 6-month interval (86,5Hz) also showed an increase in F0 variation when compared to the no-amplification and hearing aid situations, however, the variation was less and possibly more normalized, than observed during the 3-month interval.

Segmental features

- **Vowels**

Due to variations in *vowel duration* for each of the vowels within the three cochlear implant evaluation intervals, a mean vowel duration for each of the eight vowels during the cochlear implant intervals was calculated. The results of the evaluation of *vowel duration* presented in Table 4, did not indicate significant

Table 1. Sentence duration (seconds) for sentences across various auditory input situations.

Sentence number	N.A.	H.A.	CI-O	CI-3	CI-6	Mean values CI 0, 3, 6
1	0,8719	0,9750	0,9937	0,9031	0,8844	0,927
2	1,153	1,272	1,438	1,472	1,387	1,432
3	1,700	1,727	2,425	1,993	1,878	2,098
4	1,537	1,691	1,628	1,600	1,547	1,591
5	1,237	1,575	1,456	1,359	1,322	1,379
6	0,9469	0,9688	0,9562	1,031	0,9312	0,972
7	0,8031	0,9600	1,006	0,9750	0,9125	0,964

Table 2. Highest amplitude peaks (dB) for stressed words in sentences across various auditory input situations.

Sentence number	N.A	H.A	CI-0	CI-3	CI-6
1	25	35	33	37	37
2	24	32	30	37	35
3	37	34	31	36	37
4	34	30	33	36	35
5	34	34	37	40	41
6	33	35	32	39	37
7	35	38	36	37	37
Mean amplitude peaks (dB)	31,7	34	33,1	37,4	37,0

differences between the various auditory input situations. For all the vowels examined except for the vowel /y/, however, when a mean value for the 0-, 3- and 6-month evaluations was calculated, the latter did show a decrease in vowel duration when compared to either the no-amplification or hearing aid condition.

The *formant frequencies* of the vowels analyzed, i.e., F1 and F2, presented in Table 5, did not differ from one another significantly across the various auditory input situations. Compared to the normal values of F1 and F2 in the vowels of male Afrikaans speakers, (Van der Merwe, Groenewald, Van Aardt, Tesner & Grimbeek, 1993), the formant frequencies of four of the vowels i.e. / i /, / a /, = / u / and / ɛ / fell within the normal limits. In the four remaining vowels i.e. / œ /, / ɔ / and /œ/ examined except for / y /, the F2 values fell within the normal limits for these vowels. The F1 values, however, were measured at higher frequencies than the normal limits for F1. The results in the present study did, however, indicate that the F1 and F2 values did remain relatively consistent across the various auditory input situations as was observed with the other four vowels examined.

- **Consonants**

As can be seen in Table 6 for the majority of the consonants examined in the present study, the use of the cochlear implant did show an increase in the *relative amplitude peaks* measured for consonant production i.e., plosives and fricatives. The relative amplitude peaks for the consonants in the various auditory input situations ranged from 0-46dB in the no-amplification situation, 0-50dB in the hearing aid situation, 19-51dB in

Table 3. Minimum and maximum fundamental frequency values (Fo-Hz) and difference in fundamental frequency (Δ Fo) for sentences across various auditory input situations.

Sentence number	Max Fo Min Fo	N.A	N.A Δ Fo	H.A	H.A Δ Fo	CI-0	CI-0 Δ Fo	CI-3	CI-3 Δ Fo	CI-6	CI-6 Δ Fo
1	Max	162	45	157	70	134	34	243	137	222	103
	Min	117		87		100		106		119	
2	Max	132	43	129	45	124	38	204	113	182	80
	Min	89		84		86		91		102	
3	Max	170	89	150	62	129	48	213	115	213	89
	Min	81		88		81		98		124	
4	Max	144	28	128	30	138	35	182	56	186	69
	Min	116		98		103		126		117	
5	Max	179	73	165	72	186	89	262	176	256	149
	Min	106		93		97		86		107	
6	Max	144	27	142	42	124	23	196	79	165	54
	Min	117		100		101		117		111	
7	Max	162	43	167	60	144	44	222	99	204	62
	Min	119		107		100		123		142	
Mean difference in Fo			49,7		54,4		44,4		110,7		86,5

Table 4. Vowel duration (seconds) for vowels across various auditory input situations

Word	Vowel	N.A.	H.A.	CI-0	CI-3	CI-6	Mean
mier	/i/	0,4812	0,4016	0,4187	0,2469	0,3125	0,3260
waak	/a/	0,2187	0,3719	0,2813	0,3875	0,3562	0,3416
duur	/y/	0,3375	0,3156	0,4812	0,3312	0,4590	0,4238
dop	/ɔ/	0,1469	0,1344	0,1500	0,1312	0,1094	0,1302
toer	/u/	0,5875	0,5594	0,4906	0,4094	0,4031	0,4343
pen	/ɛ/	0,1656	0,1563	0,1781	0,1187	0,1156	0,1374
rug	/œ/	0,1219	0,1656	0,1594	0,1281	0,1563	0,1479
mis	/ə/	0,0781	0,1312	0,1344	0,0962	0,0734	0,1013

Table 5. Formant frequencies - Hz (F_1/F_2) for vowels across various auditory input situations

Word	Vowel	F_1/F_2	N.A	H.A	CI-0	CI-3	CI-6	Mean Ci 0, 3, 6	Normal F_1/F_2
mier	/i/	F_1	300	260	300	300	280	293	245
		F_2	2180	2190	2160	2320	2380	2287	2186
waak	(a)	F_1	760	620	770	640	600	670	679
		F_2	1180	1160	1180	1220	1060	1153	1113
duur	/y/	F_1	260	240	220	390	290	300	*
		F_2	2180	2160	2080	2310	2470	2287	*
dop	/ɔ/	F_1	580	280	540	540	590	557	373
		F_2	1020	1080	1180	1040	1040	1087	805
toer	/u/	F_1	260	250	260	390	360	337	266
		F_2	780	920	780	800	1010	863	961
pen	/ɛ/	F_1	500	480	500	560	530	530	353
		F_2	1960	2040	2060	2100	2000	2053	2055
rug	/œ/	F_1	640	540	560	580	580	573	429
		F_2	1280	1200	1240	1160	1040	1147	1314
mis	/ə/	F_1	580	540	540	540	600	560	507
		F_2	1400	1520	1480	1470	1330	1427	1514

Table 6: Relative amplitude peaks (dB) for consonants in CVC word combinations across various auditory input situations

Word	Consonant	Position	No amplification	Hearing Aid	CI 0 months	CI 3 months	CI 6 months
lied	/t/	Final	0	38	23	35	48
pit	/t/	Final	29	18	31	47	48
loop	/p/	Final	0	19	22	23	21
druip	/p/	Final	0	0	19	31	29
bek	/k/	Final	26	0	20	37	39
rok	/k/	Final	0	20	21	33	36
kous	/s/	Final	31	43	48	44	48
mos	/s/	Final	44	43	48	44	49
rug	/x/	Final	33	43	27	38	36
saag	/x/	Final	29	35	34	33	31
sag	/s/	Initial	43	50	51	29	54
saag	/s/	Initial	46	48	48	54	52
vaak	/f/	Initial	19	34	22	34	28
vuur	/f/	Initial	33	34	26	29	32

the 0-month cochlear implant interval, 23-54dB in the 3-month interval and 21-54dB in the 6-month interval. Three of the consonant productions in the final position i.e., / t /, / k / and / p / were not produced with any audible plosive release in the no-amplification and hearing aid situations therefore having no measurable amplitude peaks i.e., 0dB.

The results of the mean *spectral frequency ranges* for the plosive energy of the plosives i.e., / t /, / p /, and / k / and the *spectral noise band frequencies* for the fricatives i.e., / s /,

/ x / and / f /, presented in Table 7, did show a narrowing of these frequency ranges for the majority of consonants evaluated in the three cochlear implant intervals when compared to the hearing aid conditions. Once again there were no measurable spectral frequency ranges (0Hz) for three of the consonants i.e., / p /, / t / and / k /, as there was no audible plosive release in the final position during the no-amplification and hearing aid conditions.

Results of the speech production evaluation using listener analysis.

The results of the listener's evaluation of the subject's speech production are presented in Table 8. The trained listeners rated the subject's spontaneous speech at the various auditory input situations, according to the rating scale used. These ratings occurred in a language laboratory.

As can be seen in Table 8 the listeners rated the subject's use of *pitch variation* as being monotone in the no-amplification, hearing aid and 0-month cochlear implant conditions. At the 3-month cochlear implant interval, the listeners rated the subject's speech as having little variation and the 6-month cochlear implant interval the listeners rated the subject's use of pitch variation as being normal. With regard to *vocal duration,* the listeners evaluated the subject's vocal duration in the no-amplification, hearing aid and cochlear implant 0-month interval as being longer than normal.

Table 7. Minimum and maximum frequencies for consonants in CVC word combinations across various auditory input situations.

Word	Consonant	Position	Minimum maximum	No Amp	HA	CI-0	CI-3	CI-6
lied	/t/	Final	Min Max	0 0	1760 8000+	2460 4900	1680 8000+	2880 6040
pit	/t/	Final	Min Max	3440 6800	1760 3160	2480 8000+	2720 8000+	3400 8000+
loop	/p/	Final	Min Max	0 0	3560 4720	1080 8000+	1160 7960	3680 6440
druip	/p/	Final	Min Max	0 0	0 0	1040 8000+	1240 8000+	980 8000+
bek	/k/	Final	Min Max	880 8000+	0 0	1060 5000	960 5600	880 6240
rok	/k/	Final	Min Max	0 0	960 4280	880 5020	680 8000+	640 3680
kous	/s/	Final	Min Max	2420 8000+	2240 8000+	2500 8000+	2720 8000+	3200 8000+
mos	/s/	Final	Min Max	2220 8000+	2360 8000+	2480 8000+	2560 8000+	3160 8000+
rug	/x/	Final	Min Max	800 8000+	760 8000+	2480 8000+	2640 8000+	2320 6960
saag	/x/	Final	Min Max	2460 8000+	880 8000+	2060 8000+	2760 8000+	2280 7440
sag	/s/	Initial	Min Max	2180 8000+	3200 8000+	1080 8000+	2800 8000+	3320 8000+
saag	/s/	Initial	Min Max	1000 8000+	3320 8000+	1060 8000+	2960 8000+	3000 8000+
vaak	/f/	Initial	Min Max	2100 8000+	3440 8000+	3480 8000+	1360 8000+	3680 8000+
vuur	/f/	Initial	Min Max	1360 8000+	3520 8000+	1620 8000+	2880 8000+	3600 7360

At the 3-month and 6-month cochlear implant intervals, the subject's vocal duration was evaluated as being normal. As far as *pausal duration* is concerned, the listeners evaluated the use of pausal duration as being primarily longer than normal in the no-amplification and hearing aid conditions. At the cochlear implant 0-month interval, two of the listeners rated the pausal duration as being normal, with the remaining listeners describing it as being either abnormally long or longer than normal. The pausal duration at the 3-month interval was evaluated by the majority of the listeners as being longer than normal. One listener judged it to be normal. At the 6-month cochlear implant interval, however, the subject's use of pausal duration was evaluated as being normal.

As can be seen in Table 8, listener two was the only listener who differed from the other listeners. The Pearson Correlation Co-efficient and t-test was used in order to determine whether or not listener two differed significantly from the other listeners, i.e., one, three and four. These results indicated that there were no significant differences between the listeners ratings and that all the listeners ratings correlated significantly with one another.

DISCUSSION

SPECTROGRAPHIC ANALYSIS

Suprasegmental features

Prior to having the cochlear implant, it was noticed subjectively that the subject was inclined to increase his utterance length. The latter being a characteristic of profoundly deaf individuals, as noted by Nickerson, (1975). Taking this into account, it was expected that when utterance length was spectrographically analyzed, the results obtained with the cochlear implant would show a decrease in duration, when compared to the no-amplification and hearing aid condition. Results obtained from the evaluation of *sentence duration* (Table 1), however, did not at first yield any significant data. In fact, the mean values calculated for the cochlear implant condition were in all instances longer than the values obtained in the no-amplification situation, as well as the majority of values obtained during the hearing aid condition. These results are in direct contrast to the sentence duration characteristics of profoundly deaf individuals. These individuals tend to speak at a slower rate than what is considered normal speed, (Waldstein, 1990). The values measured were consequently compared with the spectrograms obtained for each of the sentences in the various auditory input situations. These comparisons indicated that the reason for the lower sentence duration values in the no-amplification situation and the higher sentence duration values in the cochlear implant situations was that in many instances the plosive release of final consonants of the last words spoken in the sentences were often omitted due to the absence of auditory feedback. The utterance length measured did therefore not include these omitted plosive portions of the consonants. This resulted in shorter sentence duration measurements. During the three cochlear implant intervals the subject was aware of these final consonants due to the improved speech information being provided by the cochlear implant as well as improved auditory feedback, and the subsequent production of these final consonants productions resulted in a measured increase in the utterance length.

As far as *word stress* (amplification) within the sentences is concerned, the use of the cochlear implant resulted in an increase in the highest relative amplitude peaks for stressed words when compared to the no-amplification and hearing aid situations (Table 2). The specific words within the sentences which were stressed remained consistent throughout all the auditory input situations. The relative amplitude peaks of these words increased as the subject was receiving increasing

Tabel 8. Rating scale for listeners' evaluation of pitch variation, vocal duration and pausal duration-results

Evaluation parameters	Listeners	No-Amplification: Listeners ratings	Hearing Aid: Listener ratings	Cochlear Implant 0-months: Listener ratings	Cochlear implant 3-months: Listener ratings	Cochlear implant 6 months: Listener ratings
Pitch Variation	L.1	1	1	1	2	3
	L.2	1	2	2	3	3
	L.3	1	1	1	2	3
	L.4	1	1	1	2	3
Vocal Duration	L.1	2	2	2	3	3
	L.2	2	2	2	3	4
	L.3	2	2	2	3	3
	L.4	2	2	2	3	3
Pausal Duration	L.1	2	3	3	2	3
	L.2	1	2	2	2	3
	L.3	2	2	1	2	3
	L.4	2	2	3	3	3

amounts of intensity information via the cochlear implant. These alterations in loudness are coded by the multichannel cochlear implant as changes in current level, (Tobey & Hasenstab, 1991). An individual's ability to make use of intensity variations within utterances prevents the tendency to become monotone and reinforces the normal patterns of intonation in speech, (Iler-Kirk & Edgerton, 1983).

In terms of the *pitch variations in F0*, there appeared to be an over compensation in the use of varying fundamental frequency at the 3-month interval, with a slight decrease in variation at the 6-month interval, resulting in a more normalized version of fundamental frequency variations. The subject was, therefore, at the 3-month interval beginning to perceive the increased spectral information being provided by the implant as well as the variations in F0 as coded by the stimulation rate delivered to a given channel, (Tobey & Hasenstab, 1991). These variations in F0 were in turn providing increased suprasegmental information required in the use of questions, as was emphasizing certain words within a sentence in order to either alter the meaning of the sentence or emphasize a specific word within the sentence, (Iler-Kirk & Edgerton, 1983). It is also interesting to note that the words in the sentences which were produced with the highest F0 pitch remained consistent throughout all the auditory input situations. These words produced with the highest F0 pitch were also the words produced with the highest amplitude peaks. These results indicate that the subject is utilizing the suprasegmental features of speech accurately with the aim of emphasizing a specific word in an utterance.

Segmental features

- Vowels

The overall decrease in *vowel duration* with the use of the cochlear implant is confirmed by the results obtained by Tartter et al., (1989) who also found a decrease in vowel length in a postlingually deafened individual during the first year of use with a multichannel cochlear implant. The decrease in vowel length can be attributed to the improved temporal coding mechanisms provided by the cochlear implant, which in turn, improve and enhance auditory feedback monitoring, implicated in regulating the phonetic precision of segmental and suprasegmental characteristics of speech, (Waldstein, 1990; Svirsky et al., 1992).

As far as the *relationship* between the *vowel formant frequencies* is concerned, the results of the F1 and F2 values across the various auditory input situations did not show any significant differences (Table 5). The relationship between the F1 and F2 values for the eight different vowels indicated that the vowel productions across the various auditory input situations occupy well defined loci as expected. These results verify the minimal changes in the relationship between F1 and F2 across the various auditory input situations, indicating relatively stable vowel productions. To further enhance the interpretation of these results, the mean F1 and F2 cochlear implant values were compared with the mean values obtained from normal hearing Afrikaans speaking male subjects, (Van der Merwe et al., 1993). The mean F1 values obtained in the cochlear implant condition for each vowel were consistently higher than the normal F1 values. Tartter et al., (1989) in their study indicated that their subjects exhibited lower values after a period of use with the cochlear implant. A possible explanation for the higher F1 values obtained in the present study, could be attributed to the fact that the subject was not a standard Afrikaans speaker. Variations from the norm are often found when a dialect of a language is spoken, (Sommerstein, 1977). By taking the overall results into account, it can therefore be assumed that the subject's profound hearing loss did not result in deviant vowel productions.

- Consonants

With regard to the relative amplitude peaks for consonants in CVC word combinations across the various auditory input situations, the most significant increases in *amplitude peaks* were for the plosive sections of the stop consonants (Table 6). These significant increases in amplitude peaks can be interpreted in terms of the **absence,** in the first instance, of the plosive releases in the no-amplification situations for the consonants / p /, / t / and / k / as well as the consonants / p / and / k / in the hearing aid situation, to the **presence** in the second instance of plosive releases for these consonants during the cochlear implant intervals. For the fricatives in the initial and final positions, the majority of amplitude peaks in either the 3- or 6-month cochlear implant conditions are higher than the amplitude peaks observed in the no-amplification or hearing aid conditions, indicating improved accuracy in consonant production. This can be attributed to two factors. In the first instance, the cochlear implant is providing increased spectral information which in turn allows the subject to perceive these consonants auditorily, thereby improving the auditory feedback mechanism of the subject's own productions, (Dorman, Soli, Dankowski, Smith, McCandless & Parkin, 1990). In the second place, the cochlear implant is resulting in increased accuracy in the articulation of consonants, which consequently results in an increase in the intensity of the production.

The *spectral frequency ranges* of the *plosive* sections of the stop consonants during the 6-month cochlear implant interval did show a decrease in the frequency regions occupied for the majority of the productions when compared with the no-amplification condition. A decrease in frequency range is a direct result of a more concentrated release of the plosive section of the stop consonant, thereby improving the accuracy of productions. Minifie (1973), mentions that the noise bursts of the stop consonants are dependent upon the volumes within the vocal tract, which participate in resonance of the source energies. These volumes are primarily determined by the vocal tract occlusion. It can therefore be assumed that the more concentrated production of the plosive sections of the stop sounds, can be attributed to the correct placing of vocal tract occlusion. The latter is a result of the improved auditory feedback mechanisms provided by the cochlear implant itself. As far as the *fricatives* are concerned, the *spectral noise bands* with the cochlear implant at the 6-month interval also showed a decrease in the frequency ranges measured for each fricative when compared to the no-amplification situation. These spectral noise band limits measured for the fricatives fell within the noise band limits of normal speakers, (Baken, 1987). The majority of the fricatives showed an increase in the minimum frequency with the use of the cochlear implant. These findings resulted in a narrowing of the spectral noise band frequencies which once again indicated the concentration of energy as a result of marked vocal tract constriction, resulting in increased accuracy of fricative production (Minifie, 1973).

- *LISTENER ANALYSIS*

The results of the listener's rating of *pitch variation* indicated that the subject was beginning to use pitch and intensity information being provided by the cochlear implant. These results are supported by Iler-Kirk & Edgerton, (1983); Dowell et al., (1985); Leder et al., (1986); and Tyler & Kelsay, (1990), who also reported improvements in voice control with the use of a multichannel cochlear implant. These improvements can be attributed to the pitch information being provided by the cochlear implant resulting in improved auditory feedback of the subject's utterances. As far as *vocal duration* and *pausal duration* are concerned, the improvements which were made could once again be attributed to the improvements in auditory feedback resulting in improved voice control and temporal resolution, (Leder et al., 1986; Tyler & Kelsay, 1990; Tartter et al., 1989). The latter improvements correlate well with the results obtained during the suprasegmental analysis.

CONCLUSION

In conclusion, the results of the spectrographic analyses indicated that the information provided by the cochlear implant resulted in the improved use of suprasegmental features by the subject. There was an overall decrease in sentence length resulting in less drawn out speech. For the sentences where there was an increase in sentence length, the presence of consonants in the final position during the cochlear implant intervals as opposed to the absence thereof during the no-amplification and hearing aid situations, provided a logical explanation for this occurrence. The use of increased word stress measured in terms of relative amplitude as well as an increase in the variation of fundamental frequency, typically resulted in less monotone and more variable speech production.

As far as the segmental features are concerned, the results of the vowel analysis indicated that the cochlear implant was providing improved auditory feedback which subsequently resulted in a decrease in vowel length over time. The relationship between the first and second formants for the various vowels did not show any significant differences across the various auditory input situations. These results were expected as the subject's vowel productions were not perceived as being deviant when subjectively compared to the same vowel productions by normal hearing individuals. The overall increase in relative amplitude peaks for the consonants investigated as well as the narrowing of the spectral frequency ranges and the spectral noise band frequencies indicated that the use of the cochlear implant was resulting in far more accurate consonant productions.

The results of the listener's analysis of speech production indicated that the multichannel cochlear implant confirmed a significant improvement in the use of suprasegmental features in the subject's speech production as perceived by the listeners. The overall improvement in the use of suprasegmental speech features can be attributed to the normalization in the use of pitch variation as well as vocal and pausal duration with the cochlear implant over time.

Finally, the "hearing" provided by the cochlear implant is considered to have two major roles in maintaining the communicative effectiveness of the production mechanisms in adults. In the first instance, self hearing helps to calibrate production mechanisms by monitoring relations between the implant user's own articulations and his/her acoustic output. In the second instance, the speaker can validate his/her acoustic output by observing the behaviour of the listeners and by detecting discrepancies between his own speech and that of the listeners, (Perkell et al., 1992).

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Appendix A. Rating scale for the listener's evaluation of pitch variation and vocal and pausal duration

Feature	Description of feature as perceived by listener				
	1	2	3	4	5
pitch variation	monotone	little variation	normal	too much variation	abnormal variation
vocal duration	abnormally long	longer than normal	normal	shorter than normal	abnormally short
pausal duration	abnormally long	longer than normal	normal	shorter than normal	abnormally short