EFFECTS OF *COCHLEAR IMPLANTATION* ON SPEECH PRODUCTION

M.C. Langereis

Effects of cochlear implantation on speech production

Effecten van cochleaire implantatie op de spraakproduktie
(met een samenvatting in het Nederlands)

proefschrift

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CHAPTER 1

INTRODUCTION

Introduction

1.1 The effect of post-lingual deafness on speech production

The literature on speech production and deafness focusses on speech production by the pre-lingual deaf. Considerably less research is directed at the effects of post-lingual deafness on speech production. The literature about the pre-lingual deaf shows very clearly that speech of the pre-lingual deaf deviates from speech of normal-hearing subjects in both the suprasegmental and the segmental aspects of speech production. In contrast, the literature about the effects of post-lingually acquired deafness on speech production is rather inconclusive. Some researchers (Lane and Tranel, 1971; Ling, 1976; Conrad, 1979; Goehl and Kaufman, 1984) suggest that post-lingual deafness does not or does hardly result in deviant speech production. For instance, Ling (1976) states:"among adults with well-established skills, feedforward and production mechanisms have become automatic and auditory information is therefore not essential". In contrast, Zimmermann and Rettaliata (1981) suggest that auditory information does play a role in maintaining the motor patterning of speech in these subjects. They show that the speech of post-lingually deafened subjects deteriorates slowly, which leaves an important role for auditory information in the preservation of normal speech production. However, the finding that lack of auditory feedback does not immediately result in an obvious deterioration of speech, suggests that motor control patterns are 'overlearned' and that many instances are needed at which the normal range of variability is exceeded without correction from auditory information before motor patterns deteriorate. Negative effects of a profound post-lingual deafness on the quality of speech production were also shown by Cowie *et al.* (1982,1983), Leder *et al.* (1987,1990), Waldstein (1990), Lane and Webster (1991) and Plant (1983,1993). It is interesting to note that in some studies (Cowie et. al, 1982; Read, 1989) considerable intersubject variability was found with respect to the degree to which the quality of speech production deteriorates. Also, some studies (Plant and Hammarberg 1983; Cowie and Douglas-Cowie, 1982) indicated that deafening prior to the twenties has many more deteriorating effects on speech production than later deafening. The negative effects of the lack of auditory feedback on speech production are seen more frequently at the suprasegmental level than at the segmental level. Nonetheless, also deficiencies at the segmental level, are found in several studies (Waldstein, 1990; Leder and Spitzer, 1990; Plant, 1993; Lane and

Webster, 1991).

In summary, post-lingual deafness can variably result in the deterioration of several aspects of speech production, providing evidence that continued auditory monitoring is of great value in speech production.

1.2 Cochlear implants

Cochlear implants are now widely accepted as an effective aid in the rehabilitation of individuals with a profound hearing loss, who have little or no benefit from conventional hearing aids. Cochlear implants consist of an internal part including one or more implanted electrodes and a receiver coil. The external part consists of a speech processor, a microphone and a transmitter coil. Cochlear implants provide auditory information by electrically stimulating the residual eight nerve fibres of deaf persons, resulting in auditory sensations. For the post-lingual deaf this means that after a period of auditory deprivation it is possible to hear sounds again. Although, these new sounds differ from the previous sensations they offer the post-lingual deaf valuable information for the recognition of environmental sounds and, in particular, for speech perception. In the past years the results obtained with the cochlear implants are very much affected by improved technologies. The early implants were based on only one electrode. The pertinent literature (Tyler, 1992; Miyamoto, 1994; Eyles *et al.*, 1995; Hinderink *et al.* 1995) shows that although these single-channel implant users derive considerable benefit from their implant, they rarely have open-set speech perception. Nowadays, most implant systems are multi-channel systems providing better speech recognition possibilities. Two different strategies can be distinguished in the speech processors of the multichannel implants. One strategy is the feature-extraction strategy, in which features known to be important for speech perception are presented through the electrodes. With the newest sound-processing strategy, the Continuous Interleaved Sampling (CIS) strategy, the amplitudes of the pulses, activating the electrodes are derived from the outputs of a set of contiguous bandpass filters. This strategy is comparable to signal processing in the normal ear. Current research (Wilson *et al.*, 1991, Dillier *et al.*, 1992; Doyle *et al.*, 1995; Battmer *et al.*, 1995; Gantz *et al.*, 1995; Kiefer *et al.*, 1996; Boex *et al.* 1996) shows that, on average, the best results are derived with the CIS-strategy.

1.3 Cochlear implantation and rehabilitation of the deaf subjects

In the Netherlands, cochlear implantation is performed in the University Hospitals of Utrecht and Nijmegen, in cooperation with the Institutes of the Deaf: Effatha (Voorburg) and IvD (St. Michielsgestel). The following criteria are used in selecting potential candidates: a speech recognition score using monosyllables of less than 15% (with optimally fitted hearing aids), no medical contra-indications, realistic expectations of what the cochlear implant has to offer and the ability to participate in the rehabilitation program.

Twenty subjects participated in this study. All subjects used the Nucleus 22 cochlear implant (Clark *et al.*, 1978; Tong *et al.*, 1981). The Nucleus 22 implant has been originally developed at the University of Melbourne in Australia. Most subjects (17) used the MSP-processor, three subjects used the older WSP version. Both speech processors extract features important for speech recognition (Skinner, 1991). These features involve voice fundamental frequency (f_0) and the frequencies and amplitudes of the first and second vowel formants. The first and second formant determine which electrodes are stimulated and the intensity at which they are stimulated, whereas the stimulation rate of the electric impulses is determined by f_0. The MSP processor also offers the Mpeak strategy. In addition to the first and second formant this strategy includes the spectral energy in three high-frequency bands (between 2 and 6 kHz). The high-frequency energy determines the stimulation of two or three basal electrodes.

The rehabilitation program in the University Hospital of Utrecht is started six weeks after implantation with the initial tuning of the speech processor. This is followed by weekly sessions for adjusting the settings of the speech processor and for one hour of auditory training. Apart from the auditory training at the hospital the implant users are stimulated to practice daily with a 'co-therapist' at home. The co-therapist is usually a relative or a friend. The auditory training is directed at both environmental- and speech sounds. In addition to explicit auditory training the combination of acoustic speech perception and speech-reading is practiced. The aim of the rehabilitation is to reach an optimal combination of the use of the auditory and visual information. The rehabilitation program is adjusted to the individual implant user. During the first year after cochlear implantation the frequency of the rehabilitation sessions is gradually decreased, depending on the progress of the individual implant user. The total duration of the rehabilitation of the subjects participating in the present study varied from 4 to 18 months.

1.4 Perception with the Nucleus 22 cochlear implant

Although the relation between speech perception and speech production is not the subject of this thesis we present a short summary of the perceptual results with the Nucleus implant. Cochlear implantation with the Nucleus 22 has an enormous beneficial effect on the perception of sounds and particularly on speech perception. The results of the study (including our twenty subjects) performed in Utrecht and Nijmegen (Van de Broek *et al.*, 1994) showed that after implantation a significant increase in identification of environmental sounds was found (mean score pre-implantation 5%, mean score post-implantation 62%). In addition, the consonant-vowel-consonant (CVC) perception scores increased from a mean score of 3% pre-implantation to 23% post-implantation. Most importantly, most subjects showed a large improvement in their speech-tracking capabilities when using their implant; the mean tracking scores increased from 21 words per min pre-implantation to 70 words per min post-implantation. This means that post-implantation these subjects can understand speech at an almost normal rate. Additionally, most subjects reported that speech recognition took less effort than before implantation. These findings are in agreement with the general findings reported in the literature (e.g. Tyler *et al.* 1995). However, one should remember that this is valid only for the mean scores. Large interindividual variability in speech perception performance exists in post-lingually deafened subjects.

1.5 Preliminary evaluation of speech production by implant users and their co-therapists

In an early phase of our research we held a small interview to determine how the implant users themselves judged their speech production. Additionally, we asked their co-therapists to evaluate the speech production of the cochlear implant user. The interview was conducted for 29 implant users. (Implant users from a previous project, using a single channel implant, were also included.) The result was:

Subjects: 52% reported that they believed their speech was more intelligible
88% reported improved control of loudness

Co-therapists: 59% reported that speech intelligibility had improved
94% reported improved control of loudness

These results showed larger improvements in speech production than those presented by Cooper *et al.* (1989). Amongst 30 subjects using a single-channel implant 47% of the subjects reported a definite improvement of loudness control, 27% reported that their speech became more intelligible, 30% of the next of kin noted a small improvement in speech production and 20% a large improvement. Thus, subjectively, cochlear implant users improve their speech production as a result of the auditory feedback of the cochlear implant. This result stimulated the studies included in this dissertation.

1.6 Objectives of this thesis

Cochlear implants provide the post-lingually deaf with a renewed, but imperfect perception of their own speech. Consequently one may expect an influence of restored speech perception on their speech production. In the literature different effects of cochlear implantation on speech production are described. Effects on both suprasegmental (Kirk and Edgerton, 1983; Plant and Oster, 1986; Oster, 1987; Leder *et al.* 1987; Read, 1989; Tartter, 1989; Plant, 1993) and segmental (Tartter *et al.* 1989; Economou *et al.*, 1992; Perkell *et al.*, 1992; Plant, 1993; Lane *et al.*, 1994) aspects are reported. However, most studies are case studies or are restricted to a very limited number of subjects. The literature shows conflicting results which, however, may be due to the large interindividual differences and the limited number of subjects per study. This implies that the effects on speech production should be investigated in a large group of subjects.

On the basis of the literature and our preliminary experience we came to the primary aim of the research described in this thesis: Evaluation of the effect of cochlear implantation on speech production in a large group of twenty post-lingually deafened adults. Because the Nucleus 22 implant predominantly conveys segmental information essential for vowel identification we started to investigate the effect of cochlear implantation on vowel production. Several researchers (Tyler *et al.*, 1989; Blamey and Clark, 1990; Mülder *et al.*, 1992; Tartter *et al.* 1992) already noted that formant information from the Nucleus (WSP and MSP) is used in the identification of vowels. The f_0 information presented to the cochlear implant users stimulated the study of the effect of implantation on voice fundamental frequency. McKay and McDermott (1993) already showed that Nucleus cochlear implants users could identify intonation patterns well above chance level.

In addition to an evaluation of speech production, the aim of this research was directed at developing materials and methods for the evaluation of speech production and to compare the results of the different methods.

1.7 Contents of this thesis

In chapter 2 the effect of cochlear implantation on the production of vowel formant frequencies (the first and second formant; F_1, F_2) of eleven Dutch vowels /ɑ,ɛ,ɔ,ʌ,I,i,a,e,y,u,o/ is described. The following issues are addressed:

1. What is the effect of cochlear implantation on the frequency ranges covered by F_1 and F_2? Waldstein (1990) showed that the ranges of the vowel spaces of post-lingually deafened subjects were smaller than those of normal-hearing subjects. Therefore, we studied whether the auditory information provided by the implant resulted in larger frequency ranges of F_1 and F_2 post-implantation.
2. What is the effect of implantation on the deviation of F_1 and F_2 from the norm values?
3. Are vowels produced with less variability after implantation, implying a more stable production?
4. What is the effect of implantation on the ability to make phonological contrasts among vowels? A larger contrast among vowels could possibly result in better intelligibility of the vowels.

In chapter 3 the effect of cochlear implantation on vowel intelligibility is described. The following aspects are addressed:

1. The effect of cochlear implantation on vowel intelligibility in a noisy background. We presented the speech materials from all twenty subjects to listeners in a noisy background to avoid near-perfect intelligibility scores for the better subjects.
2. The effect of cochlear implantation on vowel intelligibility in a quiet background for seven poorly performing subjects.
3. The question of which acoustic features of vowels produced by the post-lingual deaf are used by the listeners in vowel identification.
4. The relation between the vowel intelligibility scores and the objective formant measurements, described in chapter 2.

In chapter 4, the effect of cochlear implantation on voice fundamental frequency of utterances of post-lingually deafened adults is described. The limited literature is inconclusive as to the question of how voice fundamental frequency changes after cochlear implantation. There seems to be a trend toward the voice fundamental frequency characteristics found for normal-hearing subjects. Given the large intersubject variability in the degree to which the quality of speech production deteriorates in the post-lingually deaf we may expect large variability in the effect of cochlear implantation on voice fundamental frequency.

Chapter 5 describes an experiment on nasality as affected by cochlear implantation. The literature reporting mainly perceptual judgements suggests that post-lingual deafness has a variable effect on nasality. We studied the effect of post-lingual deafness and of cochlear implantation on nasality using the nasometer (Kay Elemetrics).

In chapter 6 the results of a perceptual judgement experiment are described. In this study we evaluate the effect of cochlear implantation on speech quality using perceptual judgements from a panel of speech therapists. Both segmental aspects and suprasegmental aspects are considered. The speech of all subjects was rated on the basis of 21 questions. In addition, this chapter describes the relation between the results from this study and from the previous ones described in chapter 2, 3 and 4.

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CHAPTER 2

CHANGES IN VOWEL QUALITY IN POST-LINGUALLY DEAFENED *COCHLEAR IMPLANT USERS*

Changes in vowel quality in post-lingually deafened cochlear implant users

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Abstract

The present study addresses the effect of cochlear implantation on vowel production of twenty post-lingually deafened Dutch subjects. All subjects received the Nucleus 22 implant (3 WSP and 17 MSP processors). Speech recordings were made pre-implantation and three and twelve months post-implantation with the implant switched on and off. The first and second formant frequencies were measured for eleven Dutch vowels (monophthongs only) in an h-vowel-t context.

Twelve months post-implantation, the results showed an increase in the ranges of the first and second formant frequency covered by the respective vowels when the implant was switched on. The increase in the formant frequency range was most marked for some subjects with a relatively small formant range pre-implantation. Also, at twelve months post-implantation with the implant switched on we found a significant shift of the first and second formant frequency toward the norm values. Moreover, at this time the results showed significantly increased clustering of the respective vowels, suggesting an improvement in the ability to produce phonological contrasts between vowels. Clustering is defined as the ratio of the between-vowel variance of the first and second formant frequency and the within-vowel variance of three tokens of the same vowel.

2.1 Introduction

A profound postlingual hearing loss is often associated with a reduction in the quality of speech production (Cowie *et al.*, 1982; Waldstein, 1990; Plant, 1983, 1993; Leder and Spitzer, 1990; Read, 1989). However, the degree to which the quality of speech production deteriorates varies considerably from one hearing impaired subject to another (Cowie *et al.*, 1982; Read, 1989). The detrimental effects of auditory deprivation on speech production are seen both at the segmental and the suprasegmental level. At the suprasegmental level Leder *et al.* (1987a) reported higher values for voice fundamental frequency (f_0), Lane and Webster

(1991) found larger f_0 deflections, Ball *et al.* (1990) reported irregular vocal fold vibration and Leder *et al.* (1987b) found greater intensity fluctuations. At the segmental level Monsen (1976) showed a reduction of the vowel space based on the frequencies of the first and second formant (F_1, F_2). The reduction was most obvious for F_2. Waldstein (1990) compared the formant frequencies of vowels pronounced by post-lingually deafened speakers to those of normal-hearing speakers. She found for all seven deafened subjects that the range of their vowel space was smaller and, in addition, that the vowels were produced with increased variability, suggesting a less stable production. Also, Waldstein found that subjects who became deaf at young age produced vowels at more deviant positions in the vowel space than those deafened at an older age. Plant (1993) had a panel listening to the speech of ten post-lingually deafened speakers and found a tendency for vowel structure to be reduced and vowel duration to be prolonged. For the consonants, Lane and Webster (1991) noted less differentiation in place of articulation of fricatives and plosives. Deviant articulation of fricatives is one of the most frequently mentioned effects of deafness on consonant production together with differences in the articulation of affricates (Lane and Webster, 1991; Cowie and Douglas-Cowie, 1983; Plant, 1984). Within vowel-consonant (VC) utterances Zimmermann and Rettaliata (1981) noticed prolonged voicing after vowels followed by a voiceless consonant. Waldstein (1990) found shortened voice-onset times for voiceless stops in initial position. Thus, post-lingually acquired deafness can result in deterioration of several aspects of speech production, providing evidence that continued auditory monitoring is important for normal speech production. This applies both to the suprasegmental and segmental aspects.

Cochlear implants return auditory feedback to post-lingually deafened people. The renewed, but imperfect perception of their own speech may change their speech production. Although this may be true for both segmental and suprasegmental aspects of speech production we will limit ourselves to the segmental aspects of vowel production. Recent studies on the effects of cochlear implantation on vowel production in post-lingually deafened people are limited to a few case studies and some studies for small groups (Boothroyd *et al.* 1988; Tartter *et al.*, 1989; Svirsky and Tobey, 1991; Economou *et al.*, 1992; Perkell *et al.*, 1992; Cummings *et al.*, 1994). Tartter *et al.* (1989) studied the speech of a post-lingually deafened teenager after using the Nucleus 22 cochlear implant (WSP processor) for one year. They found negative effects of implant use on vowel production: the vowel space had become smaller and both first and second formant frequency were lowered. Svirsky and Tobey (1991) compared vowel formant frequencies for one user of a Nucleus multichannel implant (WSP processor) when the implant was switched on and off. After switching on the implant they found a significant increase of the first formant frequencies of the vowels /æ,o/ and a significant decrease of the first formant frequencies of the vowels /3, U/. In addition, they found a significant increase of the second formant frequencies for the intermediate vowels /I,ε,o,3/ after switching on the implant while they did not find a significant change for the point vowels /i,a,u/. Economou *et al.* (1992) reported improvement in vowel production of a post-lingually deafened pre-adolescent following replacement of a single-channel implant by a Nucleus multichannel implant (WSP processor). After reimplantation there was an expansion of the vowel space, particularly in the F_2 dimension. Moreover, the F_2 frequencies changed into the direction of the norm values. Perkell *et al.* (1992) investigated vowel production of four post-lingually deafened users of the Ineraid multichannel cochlear implant. For three of their subjects they noted that the F_2 frequencies for the front vowels became more similar to the norm values. However, the F_1 frequency range was smaller for two of the subjects. Using the Speech Pattern Contrast test (SPAC) Boothroyd *et al.* (1988) examined the effect of cochlear implantation on the speech production of six post-lingually deafened subjects wearing a Nucleus implant. The effect of the Nucleus implant (WSP processor) on vowel quality appeared to be very small. For two subjects Cummings (1994) used the ratio of F_1 and F_2 frequencies. No significant differences in this ratio were found after implantation. In summary, the above results show quite a variety of effects of the use of cochlear implants on speech production within a limited number of subjects.

Several researchers have investigated the ability of cochlear implant users to perceive the spectral information of vowels and to use this information to improve vowel production. Tyler *et al.* (1989) showed that subjects with cochlear implants could utilize some spectral information for the identification of synthesized vowels. Blamey and Clark (1990), Tartter *et al.* (1992) and Mülder *et al.* (1992) reported that formant information from the Nucleus implant (WSP and MSP processors) was used favourably in the identification of vowels. Also, Dorman *et al.* (1988) found in one subject using the Symbion multichannel cochlear implant that F_1 and F_2 information was used in vowel identification. Moreover, Perkell *et al.* (1992)

showed a relation between changes in speech production in one subject and her vowel identification scores; F_2 moved to the norm position with an increase in vowel identification scores. It is obvious from the literature that post-lingually deafened cochlear implant users can utilize information from their cochlear implants to improve their speech production, although large individual differences are present.

In view of the limited information available in the literature we investigated the effect of implantation of the Nucleus 22 cochlear implant (WSP and MSP processors) on the vowel formant frequencies (F_1, F_2) in a group of twenty post-lingually deafened adults. We have limited ourselves to vowels spoken in isolated syllables because the Nucleus 22 implant conveys predominantly segmental information essential for vowel identification. Also, Maassen and Povel (1985) have shown that segmental aspects and especially vowels are more important for the intelligibility of speech than suprasegmental aspects. Since the post-lingually deafened form a very heterogeneous group we included the substantial number of twenty subjects in the present study. This study addresses both the long-term effects on vowel production at three and twelve months post-implantation and the short-term effects of switching the implant on and off.

2.2 Methods

2.2.1 Subjects

Twenty post-lingually deafened Dutch subjects (eight males and twelve females) participated in the experiment. The duration of deafness varied from 1 to 47 years, their age from 28 to 68 years. All subjects were implanted with the Nucleus 22 cochlear implant. Seventeen subjects used the MSP processor and three subjects the WSP version. After implantation the subjects received auditory training only; no explicit speech therapy was given. Table 1 provides additional information about the subjects.

2.2.2 Materials

For all subjects speech recordings were made before implantation, three

Table 1. Subject and implant characteristics ordered according to gender and duration of deafness

	gender	age	etiology	duration of deafness in years	number of active electrodes 3m	12m	mean dynamic range (dB) 3m	12m	stimulus strategy 3m	12m	CVC phoneme score (%) 3m	12m
1	m	29	meningitis	1	22	21	8.3	13.2	$f_0/F_1/F_2$	$f_0/F_1/F_2$	54.0	47.6
2	m	64	progressive	1	19	18	7.0	10.2	mpeak	mpeak	55.9	40.7
3	m	51	otosclerosis	3	22	22	5.3	4.7	mpeak	mpeak	6.9	27.9
4	m	28	meningitis	9	20	20	3.3	4.7	mpeak	mpeak	19.0	28.5
5	m	29	meningitis	12	22	22	8.0	8.0	mpeak	mpeak	27.4	37.5
6	m	32	meningitis	22	11	11	9.9	9.5	$f_0/F_1/F_2$	f_0/F_2	11.3	9.2
7	m	33	meningitis	24	22	22	10.3	13.9	$f_0/F_1/F_2$	$f_0/F_1/F_2$	4.3	27.6
8	m	51	meningitis	40	22	22	4.9	5.6	mpeak	mpeak	0.0	21.5
9	f	65	otosclerosis	2	16	16	4.9	4.3	mpeak	mpeak	13.0	23.8
10	f	52	meningitis	3	20	15	7.6	7.4	mpeak	mpeak	28.5	28.8
11	f	40	otitis	4	21	16	4.4	1.2	mpeak	mpeak	13.2	27.1
12	f	37	progressive	5	18	18	2.8	2.1	mpeak	mpeak	32.5	35.9
13	f	33	unknown	5	18	14	5.3	3.5	mpeak	$f_0/F_1/F_2$	2.7	3.5
14	f	49	otosclerosis	6	20	20	3.5	3.5	mpeak	mpeak	35.1	30.0
15	f	54	unknown	7	22	22	4.3	4.3	mpeak	mpeak	45.8	43.1
16	f	68	unknown	8	22	20	4.5	2.8	mpeak	$f_0/F_1/F_2$	22.6	22.3
17	f	40	progressive	11	20	20	3.9	3.0	mpeak	mpeak	36.0	41.5
18	f	43	otitis	39	17	14	0.8	1.2	mpeak	mpeak	5.5	10.4
19	f	56	unknown	41	16	12	1.6	2.8	mpeak	mpeak	9.4	13.0
20	f	57	meningitis	47	20	20	2.3	3.2	mpeak	mpeak	2.7	11.8

All subjects have an MSP, except for subject 1,6 and 7, who have an WSP processor.

months post-implantation and twelve months post-implantation. At the three and twelve month sessions speech was recorded with the implant switched on and off. In the off-condition the subjects did not use their implant during the half-hour period prior to the measurements. The order of the on- and off- conditions in recording the syllables was counterbalanced across all subjects.

The speech material consisted of three utterances of the monophthongs /ɑ, ɔ, ʌ, I, i, a, e, ɛ, y, u, o/ in a fixed order in an 'h-vowel-t' context (hVt). The diphthongs /ɛi,au,oey/ were not included in this study because of the marked dynamic behaviour of their formants. The subjects were instructed to read the syllables aloud at a relaxed pace. The subject was sitting in a chair with the microphone (Sennheiser, MD 421 HL) at a distance of 30 cm. Analogue recordings were made with a Revox A77 tape recorder (bandwidth 20 kHz) in a sound-treated room.

2.2.3 Analysis

The recorded signal was digitized (10 kHz sampling rate, 14 bit resolution) and analyzed applying Entropic software (Entropic Speech Processing System, Entropic Research Laboratory, Inc.) running on a SUN workstation. We segmented the vowels with an interactive speech editor and calculated the first and second formant frequencies in 10-ms steps over the entire vowel duration, using a 12th order LPC analysis with a 50-ms Hamming window. When the LPC analysis failed to locate either F_1 or F_2 the order of analysis was increased to 20. Even with the enhanced analysis, the LPC-algorithm failed to identify either F_1 or F_2 in 9% of the cases. In these cases we calculated the formant frequencies over subsegments of the vowel, leaving out those subsegments in which one of the formant values was not located. Especially for the /u/ and /ɔ/ F_2 was missed relatively often. In addition, formant analysis of hoarse voices of some subjects was troublesome.

2.3 Results

2.3.1 Frequency range of F_1 and F_2

To study the effect of implantation on the ranges of frequency covered by the formant frequencies F_1 and F_2 of the eleven vowels we used the standard deviation to express this range. It was calculated for the twenty subjects individually in the five conditions: pre-implantation and three and twelve months after implantation with the implant switched on and off (Table 2). A significant change in this range with respect to the pre-implantation condition per subject is indicated in Table 2 (F-test, df1=df2=30).

*Table 2. Range of the first and second formant frequencies in Hz of the mean vowel positions per subject before implantation (pre) and three (3m) and 12 months (12m) after implantation with the implant switched on and off. The range is expressed in the standard deviation of the mean formant frequency of three tokens of each vowel across all vowels. (The range is the square root of the "between-vowel" variance per subject, df=30). The first 8 subjects are male, the next 12 female. The average range for normal hearing males is 159 Hz for F_1 and 508 Hz for F_2, for females 215 Hz and 606 Hz, respectively. A significant increase of the range (improvement) with respect to the pre-implantation condition is indicated by * ($p<0.05$) and ** ($p<0.01$); a significant decrease (deterioration) by ^ ($p<0.05$) and ^^ ($p<0.01$). The group results for all males and all females are root mean square values.*

subj	years deaf	F1 pre	F1 3m on	F1 3m off	F1 12m on	F1 12m off	F2 pre	F2 3m on	F2 3m off	F2 12m on	F2 12m off
1	1	126	119	115	148	134	456	393	398	512	488
2	1	146	161	143	117	135	527	529	520	474	494
3	3	252	234	240	236	223	450	410	431	476	453
4	9	80	95	87	97	76	353	397	386	458	336
5	12	126	117	128	119	134	505	440	495	505	487
6	2	273	119**	131**	121**	142**	271	224	211	252	236
7	2	489	91	91	131*	126*	356	357	377	395	387
8	40	87	46^^	74	124*	114	287	284	297	330	287
all males		134	133	135	142	141	411	389	401	434	407
9	2	229	257	244	250	188	479	547	527	550	515
10	3	206	220	227	170	168	598	552	541	588	604
11	4	135	143	141	128	162	517	528	500	523	505
12	5	84	136**	137**	164**	155**	553	555	538	569	577
13	5	117	157	159*	150	130	341	343	353	396	363
14	6	190	181	166	207	201	541	510	511	513	527
15	7	135	136	129	166	154	524	568	504	621	569
16	8	162	167	203	224*	203	482	551	569	560	561
17	11	220	186	164	228	194	468	547	460	553	492
18	39	87	94	93	112	78	342	299	353	366	351
19	41	160	197	216	184	166	446	398	406	393	391
20	47	137	147	149	177	187*	439	508	485	464	462
all females		162	173	174	184*	169	483	500	484	514	500

This table shows that significant changes occur for only some subjects with relatively small pre-implantation formant frequency ranges as compared to the range for normal hearing Dutch subjects (the normal male F_1 range is 159 Hz, the normal male F_2 range 508 Hz; the normal female F_1 range is 215 Hz and the normal female F_2 range 606 Hz; derived from Pols (1977)). Also, Table 2 shows that the only significant change ($p=0.05$) with respect to the pre-implantation values for the group of males (F-test, $df1=df2=240$) and females ($df1=df2=360$) separately is found for F_1 of females at twelve months post-implantation with the implant switched on. Analysis of variance (CSS Statistica) of the ranges for all twenty subjects together showed a significant condition effect for both F_1 [$F(4.76)=2.7$, $p=0.04$] and F_2 [$F(4,76)=4.2$, $p<0.005$]. Subsequent posthoc-tests (Tukey HSD) indicated a significant increase ($p=0.02$) in the frequency range of F_1 in the condition twelve months post-implantation with the implant switched on versus pre-implantation and also for F_2 after twelve months with the implant switched on versus both the pre-implantation condition and the two three-months conditions (in all cases $p \leq 0.02$). The differences between the other conditions did not reach the significance level of p:0.05.

2.3.2 Deviation of F_1 and F_2 from the norm frequencies

The increase in the frequency range of F_1 and F_2 after implantation toward the normal range suggested that the formant frequencies themselves might move closer to their norm values. Therefore, we compared the present results to the mean values of 50 Dutch male norm speakers as measured by Pols (1977) and of 25 female speakers as measured by Van Nierop *et al.* (1973). Pols and van Nierop used the same hVt-context. The distances (the absolute values of the differences) between our F_1 and F_2 frequencies and the norm values were averaged across the eleven vowels in the five conditions: pre-implantation and three and twelve months post-implantation with the implant switched on and off (Table 3).

ANOVA of the data for all twenty subjects revealed a significant effect of implantation on the distances to the norm values along both the F_1 dimension [$F(4,76)=10.4$, $p<0.001$] and the F_2 dimension [$F(4,76)=2.5$, $p<0.05$]. Subsequent posthoc-tests (Tukey HSD) demonstrated for F_1 a significant decrease of the average distance at three months post-implantation with the implant switched on ($p<0.01$) and switched off ($p<0.05$) versus pre-implantation. Also, these F_1 distances were significantly reduced twelve months post-implantation with both the implant switched on and off versus pre-implantation ($p<0.001$). No significant difference was found between three and twelve month post-implantation with the implant switched on. Also, at three and twelve months post-implantation switching off the implant had no significant effect on the F_1-distances versus the respective switched-on conditions.

*Table 3. Distances in Hz between the formant frequencies measured in our subjects and in normal hearing subjects for F_1 and F_2, respectively. Data were averaged across all vowels. The conditions were pre-implantation (pre) and three (3m) and twelve months (12m) post-implantation. Values for the conditions with the implant switched off are also given. A significant decrease of the distances (improvement) with respect to the pre-implantation condition is indicated by * ($p<0.05$) and ** ($p<0.01$).*

subj	years deaf	F1 pre	F1 3m on	F1 3m off	F1 12m on	F1 12m off	F2 pre	F2 3m on	F2 3m off	F2 12m on	F2 12m off
1	1	51	51	51	30	67	127	146	131	93	118
2	1	29	30	35	45	26	108	108	94	122	83
3	3	112	87	99	99	92	171	187	191	218	187
4	9	90	96	91	85	114	252	185	179	175	274
5	12	106	104	111	83	69	108	111	88	81	72
6	22	118	59	117	91	85	387	415	407	489	446
7	24	122	108	115	85	103	262	259	265	222	210
8	40	89	119	104	52	67	385	339	366	254	316
all males		90	82	90	71	78	225	219	215	207	213
9	2	85	75	93	84	91	314	273	295	208	223
10	3	99	73	68	73	74	185	230	266	300	209
11	4	142	100	113	117	86	119	110	140	93	117
12	5	136	79	87	55	71	156	127	102	82	87
13	5	125	91	89	113	112	290	281	282	236	266
14	6	99	51	72	48	79	216	183	235	219	277
15	7	126	109	100	88	104	274	142	179	93	145
16	8	92	106	101	63	66	207	200	121	133	192
17	11	94	56	79	72	61	192	134	177	139	160
18	39	149	131	150	124	149	310	356	346	348	344
19	41	110	90	95	76	89	296	260	232	257	258
20	47	134	117	127	93	105	236	181	199	182	190
all females		116	90	98	84	91	233	206	215	191	206
Mean		105	87*	95*	79**	86**	230	211	215	197*	209

Fig. 1 displays, per subject, the distances to the norm values along the F_1 dimensions for the pre-implantation and the two post-implantation conditions with the implant switched on. This figure shows that after implantation F_1 assumes more appropriate positions in most subjects. Interestingly, in three subjects the F_1-distance increased at three months postoperatively to show improvement only after twelve months of implant use.

The deviation of the first formant frequency from the normal range for the individual vowels pre-implantation and one year after implantation with the implant switched on is graphically represented for the twenty subjects in Fig. 2[a-d]. The results of the eight male speakers are depicted in the upper half of the graph and those of the twelve female speakers in the lower half, together with the normal mean and standard deviation for the males, Pols (1977) and the females, Van Nierop (1973). The figure shows that twelve months post-implantation F_1 falls more frequently within the normal range: 48.1% pre-implantation versus 67.3% at twelve months post-implantation for both groups together.

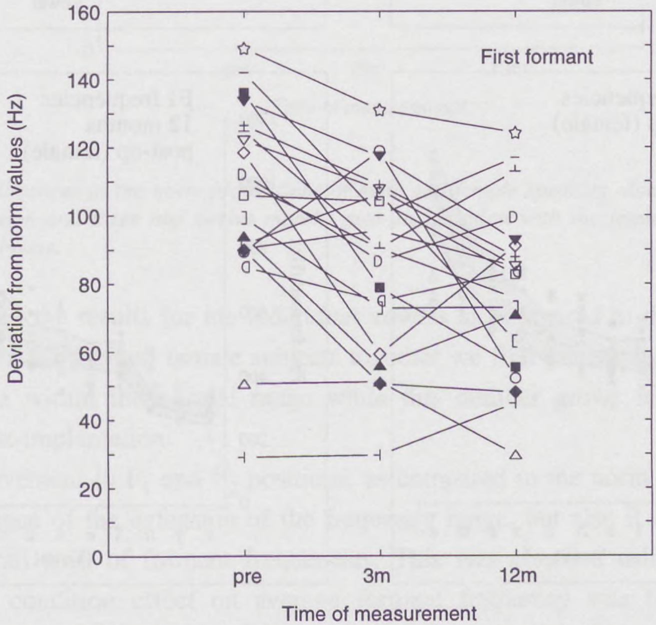

Fig. 1. The distances to the norm productions of male and female speakers along the F_1 dimension pre-implantation and three and twelve months post-implantation with the implant switched on for all twenty subjects.

For F_2 posthoc-analysis revealed a significant decrease in only the distance to the norm values twelve months post-implantation with the implant switched on versus pre-implantation ($p<0.05$), Table 3. No significant difference was found between switching on and off the implant at both three and twelve months post-implantation.

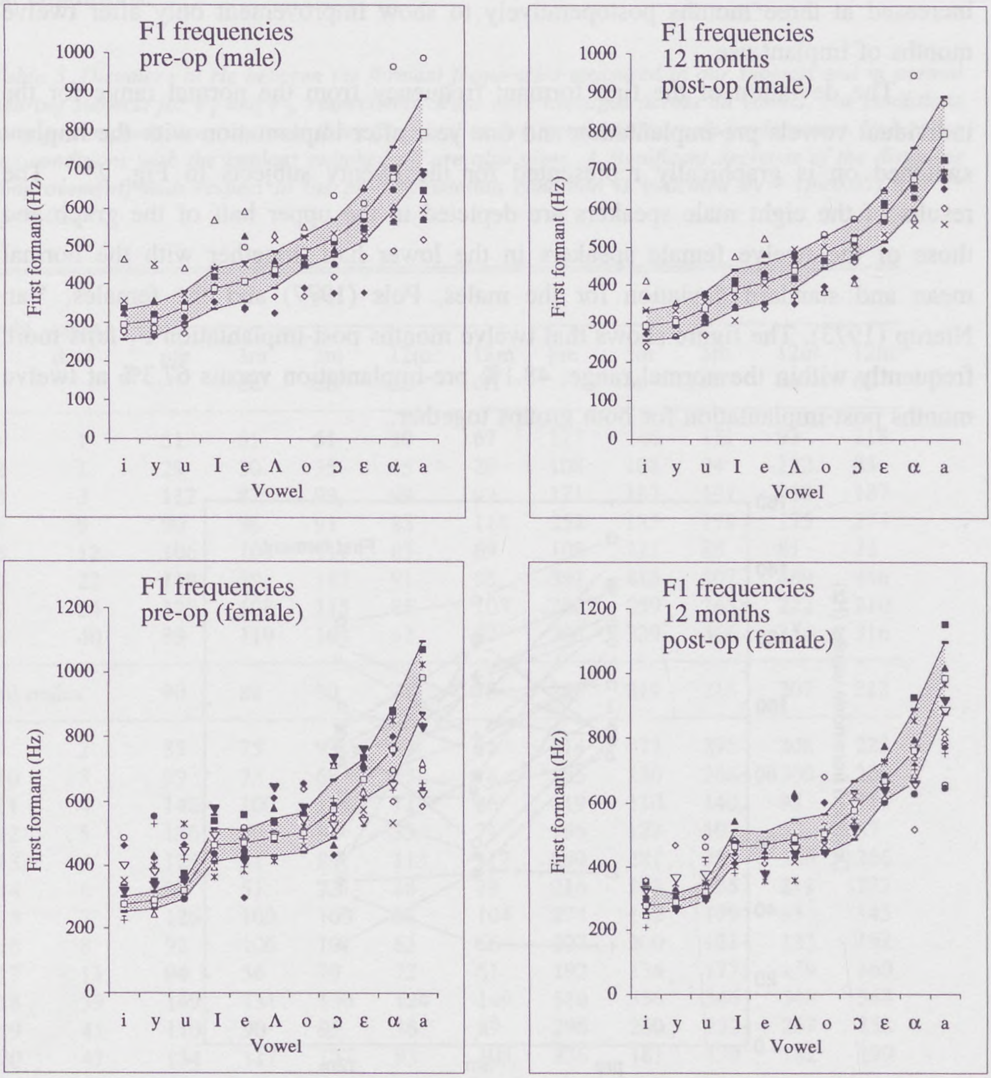

Fig. 2. First formant values for the eleven vowels for eight male and twelve female subjects, together with the normal range for the individual vowels, pre-implantation (pre-op) and one year post-implantation (post-op) with the implant switched on.

Fig. 3 shows the distance to the norm values pre-implantation and three and twelve months post-implantation with the implant switched on, averaged across the eleven vowels.

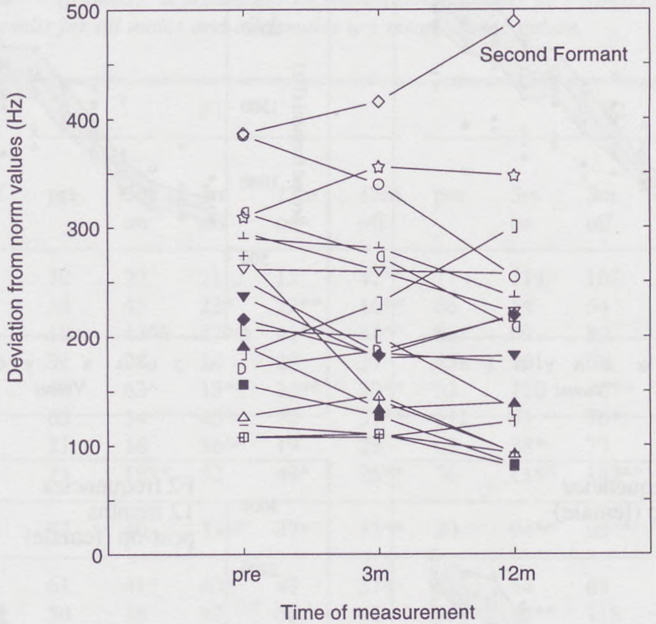

Fig. 3. The distances to the norm productions of male and female speakers along the F_2 dimension pre-implantation and three and twelve months post-implantation with the implant switched on for all twenty subjects.

Fig. 4 shows the results for the individual vowels as compared to the normal range. For the twenty male and female subjects together we find pre-implantation 46.3% of the F_2 data within the normal range while this number grows to 63% at twelve months post-implantation.

This improvement in F_1 and F_2 positions, as compared to the norm values, could be a consequence of the extension of the frequency range, but also it could be a result of an overall shift of formant frequencies. This was checked using ANOVA. No significant condition effect on average formant frequency was found. Thus, the improvement in F_1 and F_2 positions is a consequence of the extension of the frequency range rather than an overall shift in formant frequencies.

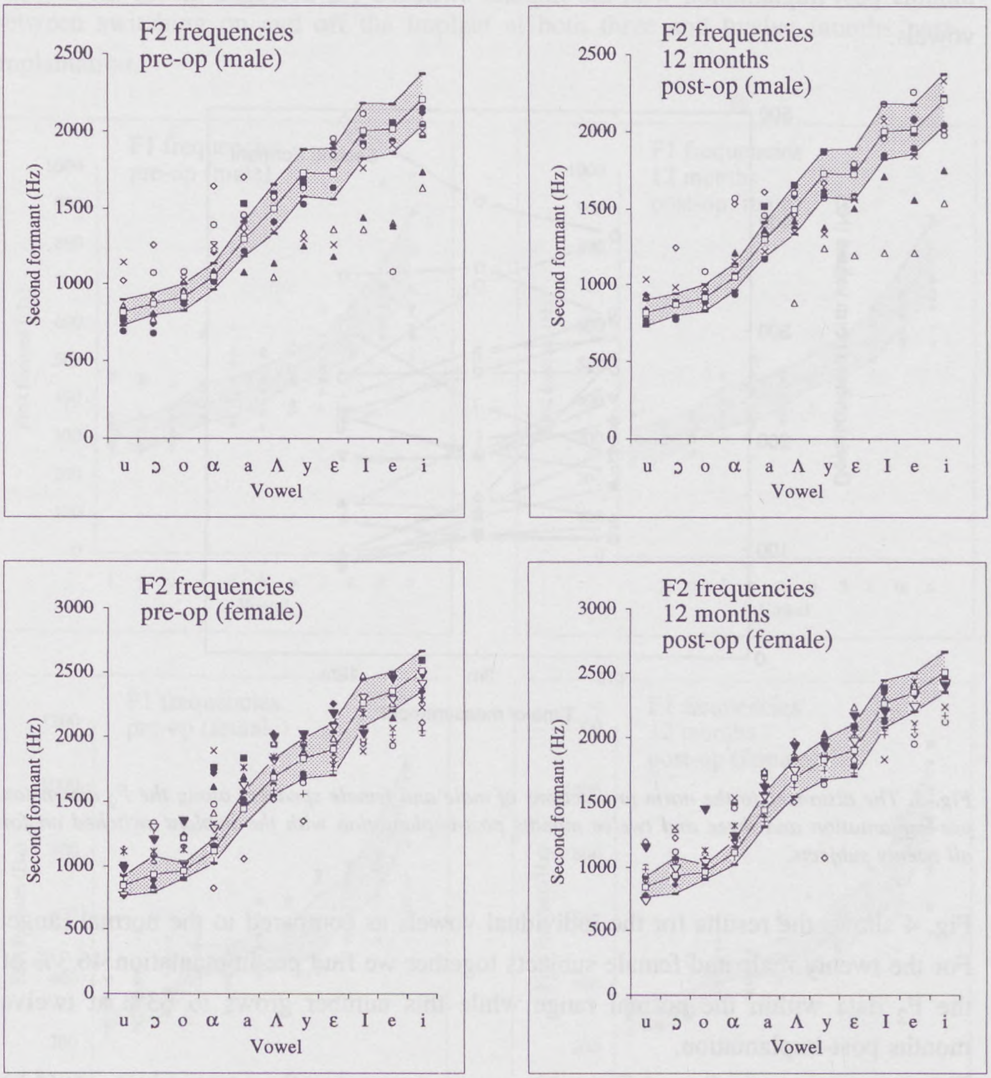

Fig. 4. Second formant values for the eleven vowels for eight male and twelve female subjects, together with the normal range for the individual vowels, pre-implantation (pre-op) and one year post-implantation (post-op) with the implant switched on.

*Table 4. Variability in first and second formant frequencies in Hz based on three tokens of each vowel per subject before implantation (pre) and three (3m) and 12 months (12m) after implantation with the implant switched on and off. The variability is expressed in the square root of the within-vowel variance per subject and per vowel, df=22. The first 8 subjects are male, the next 12 are female. A significant decrease of the variability (improvement) is indicated by * (p<0.05) and ** (p<0.01); a significant increase (deterioration) by ^ (p<0.05) and ^^ (p<0.01). The group results for all males and all females are mean square values.*

subj	years	F1					F2				
	deaf	pre	3m on	3m off	12m on	12m off	pre	3m on	3m off	12m on	12m off
1	1	20	22	21	15	47^^	77	119^	108	49*	108
2	1	38	45	23*	22**	16**	66	54	54	57	61
3	3	18	43^^	37^^	41^^	44^^	60	69	80	93^	70
4	9	31	28	24	23	37	83	101	68	84	159^^
5	12	40	63^	13**	23**	20**	92	120	40**	33**	63*
6	22	63	54	43*	70	37**	111	93	76*	122	124
7	24	21	16	36^^	19	26	63	38*	77	61	62
8	40	71	19**	52	49*	26**	76	118^	182^^	107	71
all males		42	40	33**	37*	33**	80	94^^	95^^	81	96^^
9	2	61	41*	40*	49	37*	52	54	69	65	54
10	3	50	36	37	58	40	96	47**	118	99	63*
11	4	36	53^	31	46	69^^	82	82	99	49**	83
12	5	35	25	37	51^	73^^	76	78	146^^	60	72
13	5	24	54^^	65^^	32	66^^	52	52	64	66	99^^
14	6	45	42	32	33	59	140	77**	94*	84**	83**
15	7	69	59	64	52	81	148	162	133	61**	80**
16	8	66	49	25**	42*	16**	72	74	55	50*	63
17	11	43	41	55	32	39	51	81^	92^^	84^	54
18	39	36	60^^	56^	40	46	44	94^^	108^^	48	90^^
19	41	67	60	55	52	48	99	129	85	101	105
20	47	59	31**	54	23**	59	101	41**	57**	62*	51**
all females		51	47	48	44	51	91	88	97	71**	77**

2.3.3 Variability in formant frequency

It is interesting to find that the formant frequencies move to their norm values, but good speech intelligibility does not necessarily require an "average" speaker. Among normal hearing speakers there is considerable interindividual difference in formant frequencies (Pols, 1977), which does not effect speech intelligibility at all. As a supplementary measure of vowel quality we therefore introduce the variability in formant frequency when the vowel is repeatedly uttered by the same speaker.

Table 4 shows the standard deviations of the F_1 and F_2 frequencies for the three repetitions of the individual vowels. The data are averaged across the eleven vowels. Prior analysis of variance showed that there was no systematic effect of the order in which the three tokens of one vowel were spoken. Thus, Table 4, based on the within variance, gives an unbiased estimate of the within-vowel variability. Per subject a significant difference with respect to the pre-implantation condition is, as in Table 2, indicated by * or ** for improvements (smaller variability) at the p=0.05 and p=0.01 level, respectively and by ^ and ^^ for deteriorations. The tests are again based on the F-ratios (df1=df2=22). Table 4 shows that relatively large pre-implantation variability may decrease after implantation but also that relatively small pre-implantation variability may increase. For the males there is significant reduction in F_1 variability, for the females in both F_1 and F_2 variability after implantation. F_2 variability in the males, however, increases.

2.3.4 Variability in formant frequency per vowel

Having noticed a decreased variability in formant frequencies after implantation we became interested in whether or not this improvement was related to specific vowels. Therefore, we computed the standard deviations of the F_1 and F_2 frequencies for the three tokens of each vowel averaged across the twenty subjects. The results are presented in Table 5. Per vowel a significant difference with respect to pre-implantation is indicated by * or ** for improvements at the p=0.05 and p=0.01 level and by ^ and ^^ for deteriorations. At twelve months post-implantation with the implant switched on we found a decrease in F_1-variability for the vowels /y,u,I,ɔ/. For F_2 we noted a decrease in the variability for the vowels /o,ɔ,ɛ,ɑ/. However, we found an increase in variability for the vowel /i/, considering F_1 and for the vowel /e/, considering F_2. Switching the implant off at twelve months post-implantation resulted in an increase in variability for the vowel /ɔ/, considering F_1 and for the vowels /ʌ,i/, considering F_2.

Generally, the standard deviation of the formant frequencies increases with the frequency of the formant itself. However, Table 5 shows relatively large F_1 variability for /y,u,I,ɔ/ pre-implantation. These vowels, in particular, showed decreased variability after implantation. Although less obvious in Table 5, a similar relation may hold for F_2.

*Table 5. Variability in first and second formant frequencies in Hz based on three tokens of each vowel per subject, averaged across all subjects before implantation (pre) and three (3m) and twelve months (12m) after implantation with the implant switched on and off. The variability is expressed in the square root of the within-vowel variance per vowel and per subject, df=40. A significant decrease of the variability (improvement) is indicated by * (p<0.05) and ** (p<0.01); a significant increase of the variability (deterioration) by ^ (p<0.05) and ^^ (p<0.01).*

vowel	F1					F2				
	pre	3m on	3m off	12m on	12m off	pre	3m on	3m off	12m on	12m off
i	24	35^	20	33^	30	64	81	61	67	122^^
y	61	32**	41**	27**	39**	82	117^	108	75	80
u	41	34	50	32*	41	67	75	113^^	75	66
I	40	25**	41	23**	30	87	90	85	95	61*
e	28	31	31	28	27	71	90	87	96^	98^
ʌ	37	40	48^	33	44	57	57	56	46	90^^
o	48	36*	32**	46	48	91	71	96	56**	57**
ɔ	65	46*	44*	40**	70	106	67**	117	85*	99
ɛ	48	58	58	45	36	92	80	107	57**	70*
ɑ	49	46	41	58	64	114	127	97	70**	101
a	68	79	50*	68	71	100	107	112	89	66**

The measure of vowel quality based on formant frequency variability may be extended to the variability *in relation to* the frequency range spanned by the formant frequencies of the set of vowels. Thus, we computed a "normalized" vowel variability by dividing the within-vowel variability per vowel per subject by the between-vowel variability per subject. The results, averaged across all subjects, are presented in Table 6. A significant decrease in normalized variability (improvement) with respect to the pre-implantation condition is indicated by * and ** (p=0.05 and p=0.01). At three months post-implantation with the implant switched on we found a significant decrease in the normalized vowel F_1-variability for the vowels /y,u,I,o,ɔ,ɑ/. For the normalized F_2-variability we noted a decrease for the vowel /ɔ/, but we found an increase for the vowels /y,u,e/. Twelve months post-implantation with the implant switched on we found a significant decrease for the vowels /y,u,I,ʌ,ɔ,ɛ/, considering F_1 and for the vowels /o,ɛ,ɑ/, considering F_2. However, a significant increase of the normalized variability of F_2 was found for the vowel /a/. Interestingly, switching off the implant at twelve months post-implantation resulted in an increase of F_1-variability for the vowels /y,u,I,ʌ,ɔ,ɑ/ and in F_2-variability for the vowels /i,ʌ/.

*Table 6. Normalized vowel variability in first and second formant frequencies in Hz based on the ratio of the within-vowel variance per subject per vowel and the between-vowel variance per subject. A significant decrease of the variability (improvement) is indicated by * (p<0.05) and ** (p<0.01); a significant increase of the variability (deterioration) by ^ (p<0.05) and ^^ (p<0.01).*

vowel	F1					F2				
	pre	3m on	3m off	12m on	12m off	pre	3m on	3m off	12m on	12m off
i	0.05	0.08	0.03	0.05	0.05	0.03	0.04	0.02	0.02	0.17^^
y	0.32	0.08**	0.10**	0.04**	0.11**	0.04	0.09^^	0.08^	0.03	0.05
u	0.10	0.05*	0.11	0.04**	0.09	0.02	0.08^^	0.07^^	0.03	0.02
I	0.11	0.05*	0.11	0.02**	0.05*	0.04	0.06	0.05	0.05	0.02*
e	0.04	0.05	0.05	0.04	0.04	0.03	0.05^	0.05^	0.05	0.07^^
ʌ	0.10	0.08	0.10	0.05*	0.09	0.02	0.02	0.02	0.02	0.07^^
o	0.14	0.07*	0.07*	0.09	0.10	0.03	0.03	0.05	0.01**	0.02*
ɔ	0.20	0.08**	0.11*	0.06**	0.23	0.06	0.02**	0.06	0.04	0.05
ɛ	0.23	0.17	0.23	0.10**	0.07**	0.05	0.04	0.10^	0.02**	0.03
ɑ	0.17	0.10*	0.14	0.14	0.23	0.09	0.11	0.08	0.05*	0.06
a	0.38	0.43	0.19*	0.23	0.22	0.05	0.06	0.11	0.09^	0.03

In comparing the results of Tables 5 and 6 we note that the reduction in variability becomes more pronounced when F_1 formant frequency variability is related to the frequency range spanned by the formant frequencies of the respective vowels, suggesting an increased clustering of vowels post-implantation. However, for F_2 there is no clear evidence of increased clustering. For some vowels /y,u,e/ at three month post-implantation and for the vowel /a/ at twelve months post-implantation the change in clustering rate after implantation does not reflect the change in normalized variability.

2.3.5 The clustering rate after formant frequency normalization

The ratio of the within-vowel variability and the between-vowel frequency range may determine the probability of perceptual vowel confusions and, thus, the vowel-correct score. We define the ratio of the formant frequency range and the variability, which is the inverse of the normalized vowel variability, as the clustering rate of the vowels. The increased formant frequency range together with the reduced variability of formant frequencies after implantation, both reported above, suggest that the clustering rate may improve markedly after implantation.

Analysis of variance of the formant frequencies found for the twenty subjects together suggested that this may be true because the F-ratio of the total between-vowel variance (upon which the formant frequency range was based) and the total within-vowel variance (upon which the variability was based) increased from 30 and 84 for F_1 and F_2, respectively, before implantation to 50 and 124 twelve months after implantation with the implant switched on. However, the previous analysis for all subjects included considerable intersubject variability, for example differences between male and female voices, that are not relevant for correct vowel perception. Therefore, we normalized both formant frequencies per individual with respect to the overall means in order to be able to combine the data over subjects without introducing irrelevant intersubject variability. Averaging was based on the logarithmically transformed frequency values. The results are presented in Table 7.

Table 7. Clustering rate, the F-ratio of the between-variance and the within-variance of the formant frequencies in the conditions pre-implantation and three (3m) and twelve (12m) months post-implantation with the implant switched on and off.

	pre	3m on	3m off	12m on	12m off
F_1	30	38	43	49	33
F_2	80	73	61	109	78

Twelve months after implantation we found a considerable increase in the clustering rate, both for F_1 and F_2, when the implant was switched on. With the implant switched off, however, the clustering rate decreased to the pre-implantation values. Three months after implantation there were no marked changes in the clustering rate as compared to the pre-implantation condition, both for F_1 and F_2.

The ellipses in Fig. $5^{a\text{-}e}$ show the mean and standard deviation of the normalized F_1 and F_2 frequencies for the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. The orientation of the ellipses reflects the correlation between the F_1 and F_2 frequencies. Fig. 5 clearly shows the increase in clustering twelve months after implantation with the implant switched on.

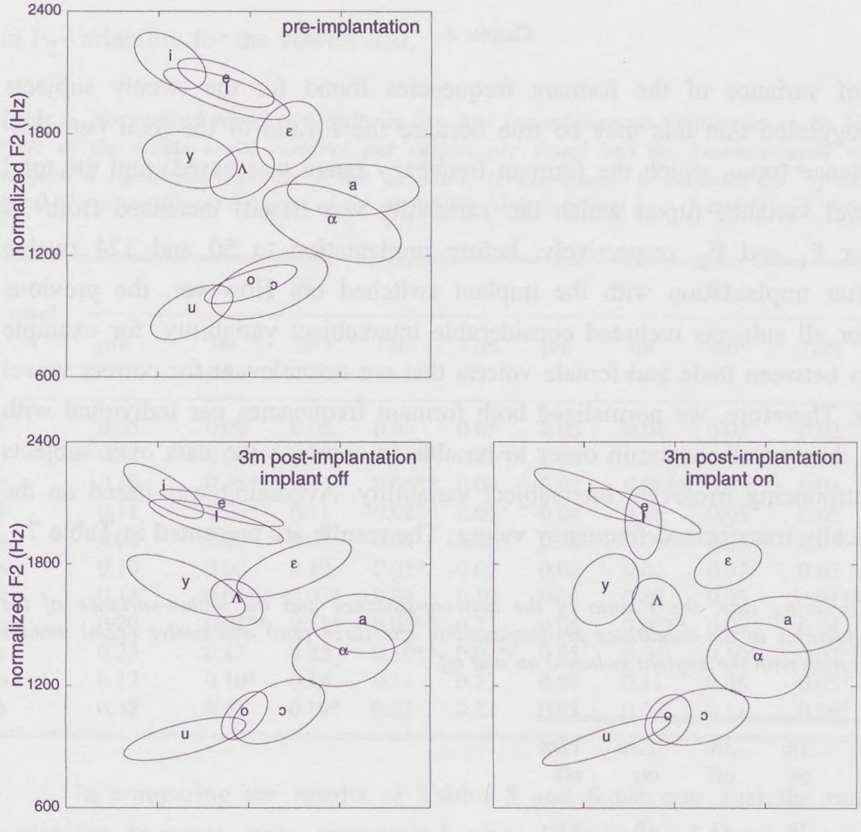

Fig. 5. Mean and standard deviation of the F_1 and F_2 frequencies after normalization for the eleven vowels, pre-implantation and at three and twelve months post-implantation, with the implant switched on and switched off. The orientation of the ellipses reflects the correlation between the two formant frequencies.

2.4 Two individual cases

In this section we will discuss the vowel spaces of two individuals. The selection of these subjects is based on the duration of deafness before implantation and the time it took to distinguish speech segments after implantation. Subject 8 had been deaf for 40 years and began to discriminate segmental aspects after as much as seven months of implant use while subject 15 had been deaf for seven years and began to discriminate segmental aspects already after two weeks of implant use.

Fig. 6 shows the vowel spaces of subject 8 pre-implantation and three and twelve months post-implantation with the implant switched on. Pre-implantation the range of the vowels is restricted in the dimension of the first formant as well as in that of the second formant. Also, the size of the ellipses shows that the vowels, especially /ʌ,y,ɛ/ are produced with great variability, particularly in the F_1 dimension. Moreover, large deviations from the norm values occur. Three months after implantation, with the implant switched on, the range of vowels is even more constricted in the F_1 dimension than pre-implantation. However, at twelve months after implantation there is an expansion in both the F_1 and F_2 dimensions, compared to the three month data and those pre-implantation. After twelve months the vowels lie closer to their norm positions and F_1 variability is reduced as compared to pre-implantation. This case fits in with the overall results discussed before.

Fig. 7 gives the vowel spaces of subject 15. Again, the mean and standard deviation of all formant frequencies, presented by the ellipses, are given for the conditions pre-implantation and three and twelve months post-implantation with the implant switched on. Pre-implantation large deviations from the norm values occur in the second formant frequencies and for some vowels /ɔ,y,o/ the variability in the F_1 and F_2 values is large. Three months post-implantation a closer-to-normal vowel configuration is emerging resulting from the lowering of the second formant frequency for the vowels /ɑ,o,ʌ/. Vowel production, however, is still variable and deviations from the norm values are still present in /y,ɛ,ɑ/. One year after implantation the vowel configuration has approached the normal structure. The vowels are produced with less variability and are closer to their norm values.

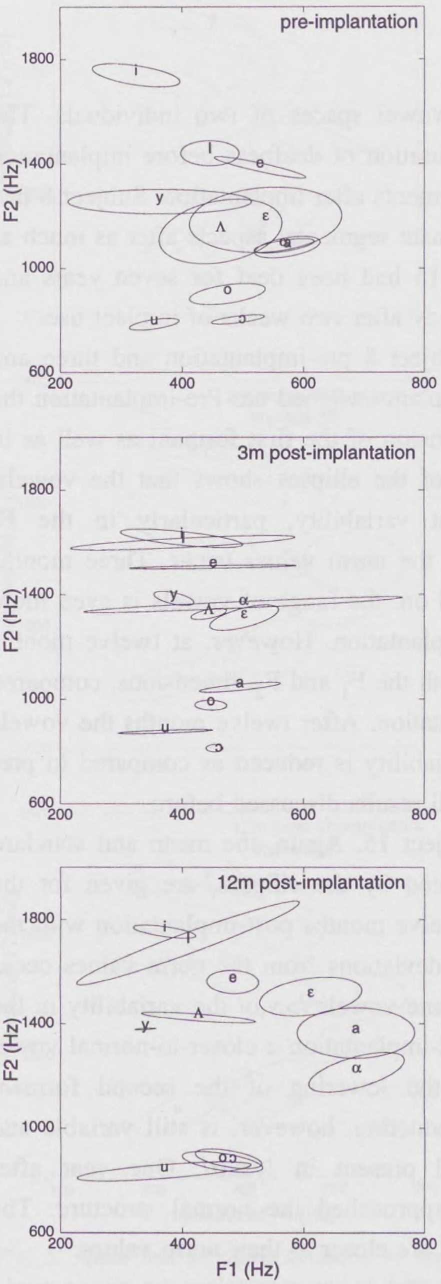

Fig. 6. Mean and standard deviation of the F_1 and F_2 frequencies for the eleven vowels of subject 8 pre-implantation and three and twelve months post-implantation with the implant switched on. The orientation of the ellipses reflects the correlation between the two formant frequencies.

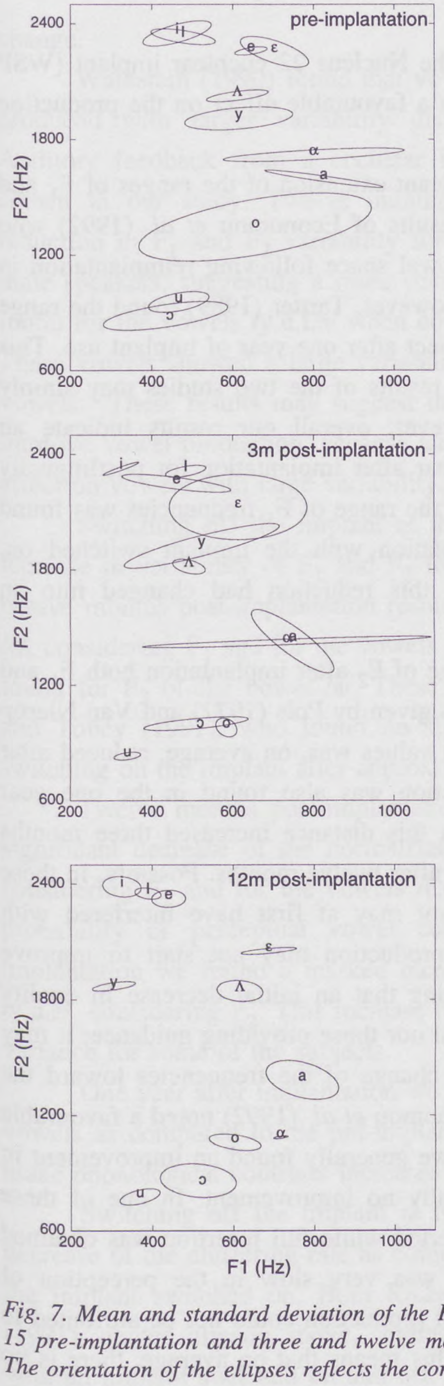

Fig. 7. Mean and standard deviation of the F_1 and F_2 frequencies for the eleven vowels of subject 15 pre-implantation and three and twelve months post-implantation with the implant switched on. The orientation of the ellipses reflects the correlation between the two formant frequencies.

2.5 Discussion

This study indicates that, in general, the Nucleus 22 cochlear implant (WSP and MSP processors considered together) has a favourable effect on the production of vowels in post-lingually deafened subjects.

After one year of implant use a significant extension of the ranges of F_1 and F_2 was found. This is consistent with the results of Economou *et al.* (1992) who reported an expansion of the range of the vowel space following reimplantation in one post-lingually deafened pre-adolescent. However, Tartter (1989) found the range of the vowel space to be reduced for one subject after one year of implant use. This study shows that the difference between the results of the two studies may simply be due to interindividual differences. However, overall our results indicate an expansion of the ranges of F_1 and F_2 one year after implantation for postlingually deafened speakers. A significant reduction of the range of F_1 frequencies was found only in subject 8 three months post-implantation with the implant switched on. Twelve months post-implantation, however, this reduction had changed into an expansion.

In addition to the extension of the range of F_2 after implantation both F_1 and F_2 frequencies moved toward the norm values given by Pols (1977) and Van Nierop *et al.* (1973). For F_1 the distance to the norm values was, on average, reduced after three months of implant use and this reduction was also found in the one year condition. However, in three of our subjects this distance increased three months post-implantation, to show improvement only after twelve months. Possibly, in these subjects the auditory feedback of the implant may at first have interfered with vowel production. This shows that speech production may not start to improve before three months of implant use, suggesting that an initial decrease in quality should not discourage the implanted individual nor those providing guidance; it may well improve later. Also for F_2 we found a change of the frequencies toward the norm positions. Perkell *et al.* (1992) and Economou *et al.* (1992) noted a favourable change of F_2 frequencies as well. Although, we generally found an improvement in F_2 position two male subjects showed virtually no improvement. In one of these speakers only eleven electrodes could be inserted while full insertion was obtained with the other subjects. The other speaker was very slow in the perception of segmental aspects. The improvement in vowel production could not be attributed to an overall shift of the formant frequencies. This means that on average, there is no shift of the whole vowel space, but rather that the relative positions of the vowels change.

Waldstein (1990) found that vowels of post-lingually deafened subjects were produced with larger variability than the vowels of normal hearing subjects. Auditory feedback from a cochlear implant may reduce this variability, as was shown in our study. Twelve months after implantation we found a significant reduction in F_1 and F_2 variability for the female speakers and only in F_1 for the male speakers, suggesting a more stable production of vowels. Improvements were found for the vowels /y,u,I,ɔ/ when considering F_1 and for /o,ɔ,ε,ɑ/, considering F_2. These vowels showed a large variability pre-implantation as compared to the other vowels. These results may suggest that explicit speech therapy is not indicated to improve vowel production, because auditory training alone already has a favourable effect on vowels with large variability.

Switching off the implant at three months post implantation resulted in an increase in variability of F_1 and F_2 for the vowel /u/. Switching off the implant at twelve months post-implantation resulted in an increase in variability for the vowel /ɔ/, considering F_1 and for the vowels /ʌ,i/ considering F_2. However, a decrease was found for F_2 of the vowel /a/. These results are not in line with those of Svirsky and Tobey (1991), who found no significant changes in the point vowels when switching on the implant after approximately 12 hours of non-use.

Twelve months post-implantation with the implant switched on we found a significant decrease of the normalized vowel variability for the vowels /y,u,I,ɔ,ε/, considering F_1 and for the vowels /ε,o,ɑ/, considering F_2, resulting in a decreased probability of perceptual vowel confusions. However, at three months post-implantation we found a marked increase in normalized variability for the vowels /y,u,e/, considering F_2. This increase resulted from a decrease in the between-vowel variance for some of the subjects.

One year after implantation we found an increase in the clustering rate of the vowels as compared to the pre-implantation results. This implies that the ability to make phonological contrasts increases post-implantation.

Switching off the implant at twelve months post-implantation resulted in a decrease of the clustering rate as compared to twelve months post-implantation with the implant switched on. Both Richardson *et al.* (1993) and Svirsky and Tobey (1991), quoted already above, studied short term effects by comparing conditions with an implant switched on and off. Richardson *et al.* (1993) found a shift in first formant frequencies between the implant switched on and off conditions in three out of five subjects, but the shift differed in direction for each subject. In addition, they found a centralization of the articulation of the front vowels /ɛ/ and /I/ in three out of five subjects after switching off the implant. Svirsky and Tobey (1991) observed a significant increase of the first formant frequencies of the vowels /æ,o/ and a significant decrease of these frequencies for the vowels /3, U/ after switching off the implant. In addition, they found a significant increase of the second formant frequencies for the vowels /I,ɛ,o,3/. The suggestion of both Svirsky and Tobey (1991) and Richardson *et al.* (1993) that auditory information may be used to adjust articulation of vowels is confirmed by our study.

Thus, although the literature (Penn, 1955; Bernstein, 1978; Read, 1989) frequently mentions that in post-lingually deafened adults vowel articulation is not or not much affected by the absence of auditory feedback, we found that the quality of vowel production of post-lingually deafened adults was affected, demonstrating that these subjects can use the spectral information of the implant effectively to improve their vowel production. It might be interesting to find out whether the new processing strategies with even better speech perception results might show more improvement in vowel production.

2.6 Conclusions

Our study shows improvements in vowel production three months and one year after implantation without explicit speech therapy. In addition to this long term effect of the implant we found, after one year of implant use, a short term decrease in vowel clustering when the implant was switched off. Comparison of the three month and twelve month post-implantation data with the implant switched on suggest that vowel production may still improve after a longer period of implant use. In some individuals auditory feedback may interfere with speech production shortly after implantation. In this case improvements may show only after a longer period of implant use.

Footnote on formant normalization

In order to be able to study effects across subjects without having to deal with increased variability due to irrelevant intersubject differences we normalized the frequencies of F_1 and F_2 with respect to their overall means on a logarithmic scale. We chose this simple scaling procedure after having seriously considered the normalization procedure proposed by Miller (1989) and used by Fourakis (1993). For two formant frequencies Miller's normalization procedure is given by:

$SR(\text{reference}) = 168\ (GMf_0/168)^{1/3}$ (1a)

$tF_1 = \log(F_1) - \log(SR)$ (1b)

$tF_2 = \log(F_2) - \log(F_1)$ (1c)

SR = sensory reference dependent on the speaker's fundamental frequency
GMf_0 = geometric mean of the speaker's fundamental frequency
tF_1 = first formant value after normalization
tF_2 = second formant value after normalization

Equation 1a shows that the sensory reference against which the formant frequencies are expressed changes with the 1/3 power of the fundamental frequency. This implies that the formant frequencies are expected to shift by 26% when the fundamental frequency changes by an octave. Adopting the average fundamental frequencies of 132 Hz for males and of 223 Hz for females from Miller (1989) for US speakers it implies that the formant frequencies of females are expected to exceed those of males by 19%. According to Pols (1977) this difference is only 10% for the Dutch language. The difference of the formant frequencies in relation to the fundamental frequency is determined by a correlation between the size of the vocal folds and the size of the articulatories. Some deafened people in our subject group produce high fundamental frequencies that are abnormal in relation to their anatomical dimensions. This suggests that a normalization based on the fundamental frequency might not be the appropriate normalization for deafened subjects. For our subjects linear regression of the logarithm of the first and second formant frequencies with respect to the logarithm of their fundamental frequency yields a power of 0.24 for F_1 and 0.15 for F_2 corresponding to a difference of only 13 and 8%, respectively. Excluding the five subjects from our results that showed abnormally high fundamental frequencies increased the power calculated by linear regression for F_1 to 0.33 and for F_2 to 0.30; well in agreement with the power of 1/3 given by Miller (1989).

In spite of the fact that the normalization of Miller is based on the American-English language which may imply another change of formant frequencies with fundamental frequency and that it is based on vowel production by normal-hearing subjects where anatomical proportions rule the relation between formant frequencies and fundamental frequency in a way not relevant to the hearing impaired we found that calculations of the clustering rate on the basis of the Miller normalization were well in line with those based on the simple scaling used in the main body of this study. Twelve months post-implantation with the implant switched on the clustering rate increases from 28 and 55 for F_1 and F_2, respectively, before implantation to 49 and 105.

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CHAPTER 3

INTELLIGIBILITY OF VOWELS PRODUCED BY *POST-LINGUALLY DEAFENED* COCHLEAR IMPLANT USERS

Intelligibility of vowels produced by post-lingually deafened cochlear implant users

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Abstract

The present study addresses the effect of cochlear implantation on the intelligibility of vowels produced by twenty post-lingually deafened Dutch subjects. All subjects received the Nucleus 22 cochlear implant (3 WSP and 17 MSP processors). Speech recordings were made pre-implantation and three and twelve months post-implantation with the implant switched on and off. Vowel intelligibility (monophthongs only) in a noisy background was determined by a panel of listeners. In addition, we measured vowel intelligibility for seven poorly speaking subjects in a quiet background.

After implantation with the Nucleus 22 device the results show that vowel intelligibility measured in a noisy background increases for most subjects. Twelve months after implantation members of the listeners panel used both first and second formant information to identify the vowels. This was also found for a subgroup of seven subjects who were performing poorly pre-implantation. For this subgroup we noticed, however, that when the vowels were presented in a quiet background listeners also used the duration of the vowels in their identification. In addition, we found that the differences between the overall result in noise and the results of the subgroup in quiet should mainly be attributed to the noise and not to aspects of poor speech productions in the subgroup.

Moreover, this study addressed the relation between the intelligibility scores and objective measurements on vowel quality of the previous study. The results showed that the vowel intelligibility scores are mainly determined by the position of the second formant frequencies.

3.1 Introduction

It is well known that speech of the prelingually deaf deviates from speech of normal-hearing subjects in various aspects. Literature about the effects of post-lingually acquired deafness on speech production, however, is inconclusive. Some researchers (Lane and Tranel, 1971; Ling, 1976, Conrad, 1979; Goehl and Kaufman, 1984) found little or no change in speech production, whereas others (Bernstein *et al.*, 1978; Zimmermann and Rettaliata, 1981; Cowie *et al.*, 1982, 1983; Read, 1989; Leder and Spitzer, 1990; Lane and Webster, 1991; Plant, 1993) found different degrees of deterioration of speech production after acquisition of a profound hearing loss.

Plant (1993) asked a panel of normal-hearing listeners to judge whether speakers were either post-lingually deafened or normal hearing. When presenting the original speech signal the listeners correctly identified the hearing status in 93% of the cases. When presented with only fundamental frequency information the score dropped to 66%. Thus, Plant (1993) concluded that "articulatory changes are an important factor in the identification of adventitiously deaf speakers". In a study by Leder and Spitzer (1990) listeners correctly identified 73% of the deaf subjects while they judged 27% to have normal hearing. For normal-hearing subjects correct identification was 97%; 3% was judged to be deaf. Leder and Spitzer (1990) also noted a negative effect of deafness on both segmental and suprasegmental aspects of speech. Significant differences between post-lingually deafened and normal-hearing subjects were found for both voice quality and articulation. Cowie and Douglas-Cowie (1983) found that speech in post-lingually deafened speakers when reading a text was less intelligible as compared to a normal hearing group. Cowie *et al.* (1982) and Read (1989) found considerable intersubject variability in the extent to which speech intelligibility decreased in post-lingually deafened subjects. Read (1989) concluded that her subjects fell into three subgroups: a group showing little or no deterioration of speech, a group with some deterioration and a group with considerable deterioration. Although suprasegmental anomalies are mentioned more frequently than segmental ones, Cowie *et al.* (1982), Waldstein (1990), Leder and Spitzer (1990), Plant (1993) have also shown deficiencies at the segmental level, *i.e.* in the production in consonants and vowels.

Cochlear implants have been used successfully in aural rehabilitation of post-lingually deafened adults. The implants, however, also partially restore the auditory control of the speech produced by the cochlear implant user. Applying objective measurements Kirk and Edgerton (1983), Plant and Oster (1986), Oster (1987), Leder *et al.* (1986), Read (1989) and Tartter (1989) reported that after implantation

speech improved at the suprasegmental level. Similarly, improvements were found at the segmental level. Effects of a cochlear implant on consonant production were studied by Boothroyd (1988), Tartter *et al.* (1989), Economou *et al.* (1992) and Lane *et al.* (1994). Effects on vowel production were studied by Tartter *et al.* (1989), Economou *et al.* (1992), Perkell *et al.* (1992), Boothroyd *et al.*(1988) and Langereis *et al.* (1997). After cochlear implantation Tartter *et al.* (1989) found a reduced vowelspace in a post-lingually deafened teenager. However, Economou *et al.* (1992) reported an expansion of the vowelspace in an implanted post-lingually deafened pre-adolescent. Perkell *et al.* (1992) noticed that the frequencies of the second formant (F_2) for the front vowels became more similar to the norm values in three out of four subjects. However, for two subjects they found a reduced first formant (F_1) range. Boothroyd *et al.* (1988) found little effect of the Nucleus-22 cochlear implant on vowel quality in six post-lingually deafened speakers. Langereis *et al.* (1997) reported significant improvements in vowel production in twenty post-lingually deafened adults after they received the Nucleus implant. One year after implantation they found an increase in clustering of the different vowels, implying an increased ability to produce phonological contrasts.
Although several studies were based on objective measurements, little research addressed the issue as to what extent the intelligibility of speech utterances of post-lingually deafened adults is affected by the auditory feedback provided by a cochlear implant.

In this study, bearing in mind the formant information (F_1, F_2) conveyed by the Nucleus 22 cochlear implant and the improvements in formant positions found by Langereis *et al.* (1997), we address the following questions:

1. What is the effect of auditory feedback provided by the Nucleus 22 implant on the intelligibility of vowels uttered by post-lingually deafened adults?
2. What is the relation between the intelligibility scores of vowels uttered by the implantees and the objective measurements of vowel quality.

To avoid near-perfect intelligibility scores for the better speakers we presented the speech materials from the implanted subjects to each listener in a noisy background. In addition, we measured vowel intelligibility for seven poorly speaking implantees in a quiet background.

Vowel identification in noise

3.2 Methods

3.2.1 Subjects

Twenty post-lingually deafened Dutch subjects (twelve females and eight males) participated in the experiment. The duration of deafness varied from 1 to 47 years. All subjects were implanted with the Nucleus 22 cochlear implant. Seventeen subjects used the MSP processor and three subjects the WSP version. After implantation the subjects received only auditory training, no explicit speech therapy was given. Table 1 provides additional information about the subjects.

3.2.2 Materials

For all subjects speech recordings were made before implantation, three months post-implantation and twelve months post-implantation with the implant switched on and off in both post-implantation conditions. In the implant-off condition the subjects were asked to turn off the implant half an hour before the measurements. The order of the recording conditions on and off was counterbalanced across all subjects.

The speechmaterial consisted of three utterances of the vowels /ɑ, ɔ, ʌ, I, i, a, e, ɛ, y, u, o/ in an 'hVt' context. The subjects were instructed to read the syllables aloud from a printed list at a relaxed pace. The subject was sitting in a chair with the microphone (Sennheiser, MD 421 HL) at a distance of 30 cm. Analogue recordings were made with a high-quality Revox A77 taperecorder (bandwidth 20kHz) in a sound-treated room.

The recordings were digitized (20 kHz sampling rate, 16 bit resolution) and the RMS level of the hVt-syllables was calculated. For each vowel we adjusted the presentation level of the hVt-syllable aiming at constant intelligibility. The adjustments were based on previous research from Bosman and Smoorenburg (1995) on vowel intelligibility and are given in Table 2 (see for the data Bosman, 1989).

Table 1. Subject and implant characteristics ordered according to gender and duration of deafness.

	gender	age	etiology	duration of deafness in years	number of active electrodes 3m	12m	mean dynamic range (dB) 3m	12m	stimulus strategy 3m	12m	CVC phoneme score (%) 3m	12m
1	m	29	meningitis	1	22	21	8.3	13.2	$f_0/F_1/F_2$	$f_0/F_1/F_2$	54.0	47.6
2	m	64	progressive	1	19	18	7.0	10.2	mpeak	mpeak	55.9	40.7
3	m	51	otosclerosis	3	22	22	5.3	4.7	mpeak	mpeak	6.9	27.9
4	m	28	meningitis	9	20	20	3.3	4.7	mpeak	mpeak	19.0	28.5
5	m	29	meningitis	12	22	22	8.0	8.0	mpeak	mpeak	27.4	37.5
6	m	32	meningitis	22	11	11	9.9	9.5	$f_0/F_1/F_2$	f_0/F_2	11.3	9.2
7	m	33	meningitis	24	22	22	10.3	13.9	$f_0/F_1/F_2$	$f_0/F_1/F_2$	4.3	27.6
8	m	51	meningitis	40	22	22	4.9	5.6	mpeak	mpeak	0.0	21.5
9	f	65	otosclerosis	2	16	16	4.9	4.3	mpeak	mpeak	13.0	23.8
10	f	52	meningitis	3	20	15	7.6	7.4	mpeak	mpeak	28.5	28.8
11	f	40	otitis	4	21	16	4.4	1.2	mpeak	mpeak	13.2	27.1
12	f	37	progressive	5	18	18	2.8	2.1	mpeak	mpeak	32.5	35.9
13	f	33	unknown	5	18	14	5.3	3.5	mpeak	$f_0/F_1/F_2$	2.7	3.5
14	f	49	otosclerosis	6	20	20	3.5	3.5	mpeak	mpeak	35.1	30.0
15	f	54	unknown	7	22	22	4.3	4.3	mpeak	mpeak	45.8	43.1
16	f	68	unknown	8	22	20	4.5	2.8	mpeak	$f_0/F_1/F_2$	22.6	22.3
17	f	40	progressive	11	20	20	3.9	3.0	mpeak	mpeak	36.0	41.5
18	f	43	otitis	39	17	14	0.8	1.2	mpeak	mpeak	5.5	10.4
19	f	56	unknown	41	16	12	1.6	2.8	mpeak	mpeak	9.4	13.0
20	f	57	meningitis	47	20	20	2.3	3.2	mpeak	mpeak	2.7	11.8

All subjects have an MSP, except for subject 1,6 and 7, who have an WSP processor.

We minimized possible effects of order of presentation by presenting the five speech production conditions in a quasi random fashion: the conditions pre, post three months and post twelve months were presented in all six possible orders. In addition, we alternated the order of implant switched on and off, yielding all together twelve orders of presentation. Further, we randomized the order of presentation of the twenty implanted speakers and the order of presentation of the respective vowels. Finally, the twelve orders of presentation of the conditions were counterbalanced across the listeners. With every new speaker and with every new speech production condition we first presented two extra stimuli to give the listeners an opportunity to familiarize themselves with the pronunciation.

Table 2. Level adjustments aiming at constant vowel intelligibility based on Dutch data from the study of Bosman and Smoorenburg (1995), see for the data Bosman (1989).

Vowel	Correction (dB)
ɑ	-1.3
a	-2.9
ɛ	-1.2
e	-2.4
I	-1.1
i	-0.4
ɔ	+2.5
u	0
o	+1.1
ʌ	+0.6
y	+2.3

The hVt-syllables were presented in noise, spectrally shaped in accordance with the speech spectrum (Wandel and Goltermann, RG1) at an average signal-to-noise level of S/N=-10 dB. This choice of S/N ratio was based on the result of a pilot experiment, involving eight normal-hearing subjects, which showed that at this S/N we would have a minimum risk of floor and ceiling effects.

3.2.3 Listeners

Twenty-four Dutch students (the number matching twelve possible orders of presentation) served as listeners. All listeners had normal hearing. They were not familiar with the hearing status of the subjects. Also, they had no prior experience in listening to speech of persons with hearing loss.

3.2.4 Procedures

At the start of the vowel identification task, the listener received a printed instruction form with information about the whole procedure. The digitized speech stimuli were played back at 50 dB SPL using a Loughborough DSP 32C system. They were mixed with the speech noise at 60 dB SPL. The combined signal was presented binaurally through Beyer DT 48 headphones. We used a closed-set identification task. The response-set consisted of all 15 Dutch vowels. Thus, also vowels not included in the stimulus set were involved, i.e. /œy,ɛi,ø,au/. The listeners responded by clicking the perceived vowel on a PC monitor using a mouse. After each response the next stimulus was presented automatically. Thus, the procedure was self paced. All listeners identified in total 3300 vowels (three utterances of each vowel x 11 vowels x 5 conditions x 20 speakers). The total length of the experiment, including three breaks of twenty minutes, was four hours.

3.2.5 Data processing

By comparing the listeners' responses to the original syllable list both correct identification scores and vowel confusions were computed. The effect of the five different conditions on the scores was tested applying analysis of variance (CSS Statistica). Whenever a significant effect was found posthoc analysis (Tukey's Honestly Significant Difference test, HSD) was performed.

Vowel confusion matrices were compiled for the five conditions. The confusion matrices were transformed into similarity matrices using an algorithm, suggested by Houtgast in an article of Klein *et al.* (1970). The similarity matrices were subjected to the algorithm of Kruskal (1964). This algorithm produces a geometrical representation of the perceptual vowel space. In this representation we find vowels that sound similar and, hence, are often confused at short distance from one another; vowels that are not confused take mutually distant positions.

3.3 Results

3.3.1 Vowel identification scores

The mean correct identification scores of twenty-four listeners for the twenty subjects pre-implantation and three and twelve months post-implantation with the implant switched on and off are shown in Fig. 1. The results of a three-way

ANOVA and subsequent post-hoc tests (HSD) are summarized in Table 3. The three main effects all are significant. Subsequent post-hoc tests (Tukey's HSD) for the factor speech-condition indicated a significant increase in identification scores three and twelve months post- implantation with both the implant switched on and off versus pre-implantation (p<0.000). However, with the implant switched on the one year post-implantation scores were significantly lower than the three-months results (p=0.02). In comparing the conditions implant switched on and off we found a significant decrease in the identification score when the implant was switched off at three months post-implantation (p<0.01). One year after implantation there was no difference between these two conditions. Additionally, we found two significant interaction effects, both involving the subject factor. There was no interaction effect between listeners and conditions.

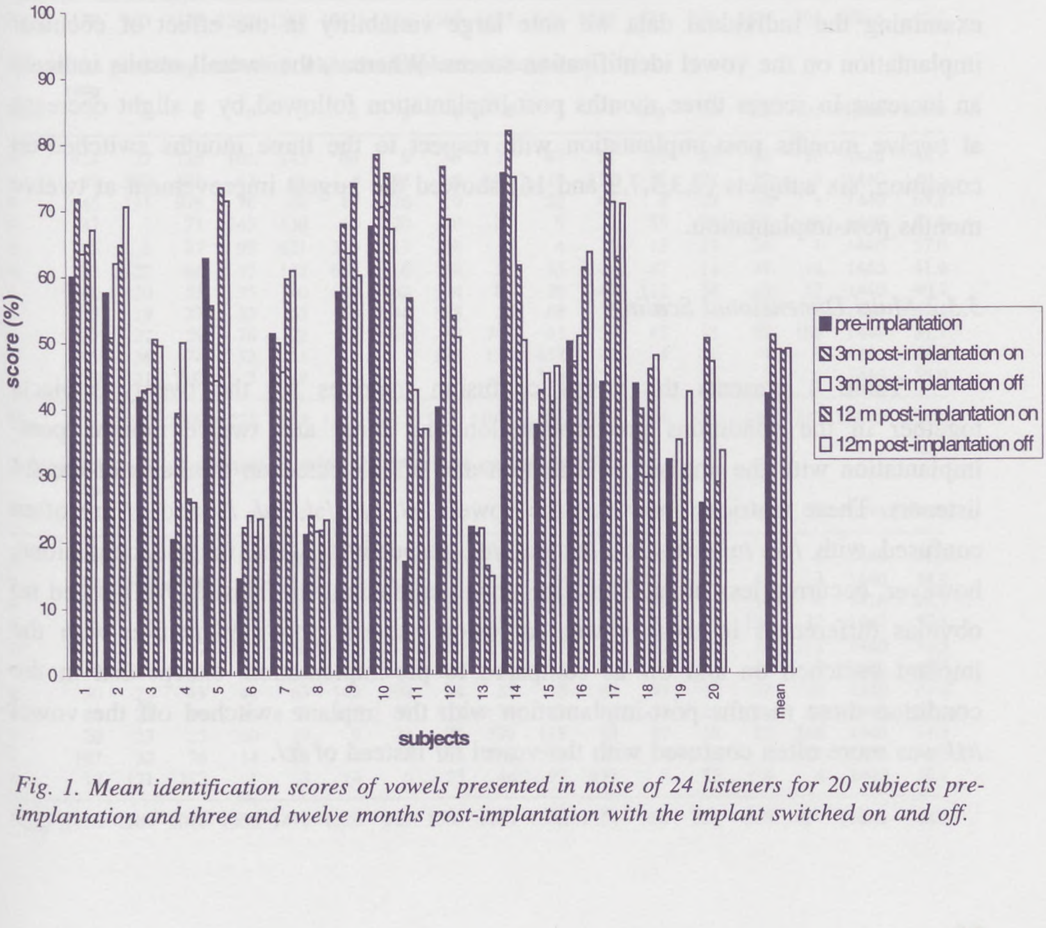

Fig. 1. Mean identification scores of vowels presented in noise of 24 listeners for 20 subjects pre-implantation and three and twelve months post-implantation with the implant switched on and off.

Table 3. Results from a three-way ANOVA, giving factors, degrees of freedom (df), F-values and p-values. Subsequent post-hoc test results (Tukey's HSD) are given for the five different speech conditions pre-implantation (pre) and three (3m) and twelve months (12m) post-implantation with the implant switched on and off. Speech materials from 20 subjects presented to 24 listeners in noise at S/N= -10 dB.

Factor	df_b	df_w	F-value	p
speech condition	4	92	75.4	.00
subjects	19	437	247.0	.00
listeners	23	1748	44.2	.00
speech*subject	76	1748	30.1	.00
speech*listeners	92	1748	1.3	.05
subject*listeners	437	1748	2.5	.00

post-hoc tests (p-values)	3m on	3m off	12m on	12m off
pre	.00	.00	.00	.00
3m-on		.00	.02	.02
3m-off			.99	.99
12m-on				.99

Although, we found a significant condition effect Fig. 1 shows that the mean increase in vowel identification scores for all subjects is small (about 9%). When examining the individual data we note large variability in the effect of cochlear implantation on the vowel identification scores. Whereas, the overall results indicate an increase in scores three months post-implantation followed by a slight decrease at twelve months post-implantation with respect to the three months switched-on condition, six subjects (2,3,5,7,9 and 16) showed the largest improvement at twelve months post-implantation.

3.3.2 Multi Dimensional Scaling

Table 4 presents the vowel confusion matrices for the twenty subjects together in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off collected on the basis of the 24 listeners. These matrices show that the vowels /ʌ/, /y/, /ɔ/, /ɑ/, /ɪ/ and /i/ are often confused with /ɔ/, /u/, /ɑ/, /ɛ/, /ɛ/ and /u/, respectively. The inverse confusions, however, occurred less often. Thus, the vowel confusions are biased. We noticed no obvious differences in these vowel confusion patterns post-implantation with the implant switched on and off as compared to pre-implantation, except that in the condition three months post-implantation with the implant switched off the vowel /ɑ/ was more often confused with the vowel /a/ instead of /ɛ/.

Table 4. Vowel confusion matrices in the speech conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. Speech materials from 20 subjects presented to 24 listeners in noise at S/N=-10 dB.

Pre-implantation

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	452	42	98	95	205	52	9	135	62	51	25	66	118	16	14	1440	31.4
y	71	438	399	70	48	4	11	22	24	27	120	45	125	22	14	1440	30.4
u	58	134	940	72	54	9	14	6	14	19	69	9	32	14	9	1440	65.3
o	39	19	70	639	164	50	18	20	21	9	4	93	89	186	19	1440	44.4
ɔ	138	4	44	121	691	236	14	53	6	7	11	22	27	65	1	1440	48.0
ɑ	83	25	71	23	131	446	166	225	33	48	45	68	26	24	26	1440	31.0
a	45	33	69	47	60	105	482	140	84	37	52	119	51	40	76	1440	33.5
ɛ	81	36	37	36	94	84	55	685	47	109	33	48	27	20	48	1440	47.6
e	50	32	65	88	57	30	55	81	608	104	66	35	74	26	69	1440	42.2
I	129	28	79	20	45	28	14	191	170	500	127	11	45	8	21	1416	35.3
i	32	112	245	11	19	17	1	11	83	80	786	5	21	9	8	1440	54.6
N_{resp}	1178	903	2117	1222	1568	1061	826	1569	1152	991	1338	521	635	430	305	15816	42.2

3 months post-implantation with the implant switched on

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	624	37	138	101	143	64	9	83	25	47	17	35	85	22	10	1440	43.3
y	59	580	323	63	11	4	18	6	22	19	115	52	132	27	9	1440	40.3
u	45	131	976	76	60	13	10	10	7	22	45	4	23	16	1	1440	67.8
o	37	7	71	743	130	40	20	10	27	9	6	55	72	207	6	1440	51.6
ɔ	136	6	27	99	821	230	13	38	4	4	1	13	13	34	1	1440	57.0
ɑ	73	22	66	37	132	603	130	158	27	33	47	47	14	37	14	1440	41.9
a	40	30	55	35	40	130	582	124	83	29	49	112	34	40	57	1440	40.4
ɛ	75	19	37	25	45	68	46	898	27	68	50	40	14	13	16	1440	62.4
e	37	22	39	76	22	27	26	63	747	63	59	43	71	37	108	1440	51.9
I	91	36	74	13	35	16	3	198	190	657	88	4	22	4	9	1440	45.6
i	39	121	200	3	9	17	5	32	40	104	850	.	11	3	6	1440	59.0
N_{resp}	1256	1011	2006	1271	1448	1213	862	1620	1199	1055	1327	404	491	440	237	15840	51.0

3 months post-implantation with the implant switched off

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	540	76	124	84	150	52	12	102	48	63	14	40	120	9	6	1440	37.5
y	82	501	384	37	14	4	4	5	22	9	125	43	193	13	3	1440	34.8
u	41	135	973	68	69	14	7	12	7	14	35	9	17	11	4	1416	68.7
o	35	4	79	721	163	46	19	14	25	.	1	52	76	193	12	1440	50.1
ɔ	111	.	37	117	756	285	9	42	1	7	3	17	15	38	2	1440	52.5
ɑ	68	17	33	32	138	616	207	127	20	27	23	61	14	48	9	1440	42.8
a	50	29	43	48	63	143	599	84	85	35	48	91	32	27	63	1440	41.6
ɛ	84	21	59	21	54	102	33	832	35	72	30	31	19	14	33	1440	57.8
e	20	23	25	60	29	9	24	72	739	119	84	37	68	22	109	1440	51.3
I	107	32	76	14	38	35	9	192	138	595	157	6	26	3	12	1440	41.3
i	12	171	212	1	3	14	6	23	46	92	837	3	12	4	4	1440	58.1
N_{resp}	1150	1009	2046	1203	1477	1320	929	1505	1166	1033	1357	390	592	382	257	15816	48.8

(Table 4 continued)

12 months post-implantation with the implant switched on

resp stim	ʌ	y	u	o	ɔ	α	a	ε	e	I	i	œy	ø	au	εi	Npres	score
ʌ	605	50	122	59	174	30	3	91	43	76	25	30	114	9	9	1440	42.0
y	61	641	464	43	14	1	3	1	23	19	72	9	82	3	4	1440	44.5
u	63	91	966	91	66	9	1	9	13	19	50	4	45	6	7	1440	67.1
o	37	9	77	708	131	37	16	17	48	4	2	57	99	183	15	1440	49.2
ɔ	109	15	60	107	801	223	7	24	6	1	17	17	17	35	1	1440	55.6
α	102	22	95	13	167	562	104	148	19	46	50	53	19	34	6	1440	39.0
a	47	29	71	46	64	143	472	127	102	36	72	99	49	37	46	1440	32.8
ε	128	17	43	7	56	94	32	829	40	73	48	27	14	9	23	1440	57.6
e	53	30	65	62	33	27	36	45	721	71	80	39	94	21	63	1440	50.1
I	120	40	104	3	54	37	9	157	137	634	99	11	22	3	10	1440	44.0
i	35	140	289	3	16	14	.	7	58	107	752	1	14	1	3	1440	52.2
N_{resp}	1360	1084	2356	1142	1576	1177	683	1455	1210	1086	1267	347	569	341	187	15840	48.6

12 months post-implantation with the implant switched off

resp stim	ʌ	y	u	o	ɔ	α	a	ε	e	I	i	œy	ø	au	εi	Npres	score
ʌ	524	63	109	86	217	37	6	143	26	55	14	27	105	19	9	1440	36.4
y	56	644	420	55	9	8	6	4	18	18	94	19	71	16	2	1440	44.7
u	48	122	1037	40	55	7	4	9	9	14	46	4	34	10	1	1440	72.0
o	37	6	91	686	143	45	24	20	35	9	8	54	69	179	10	1416	48.4
ɔ	130	10	73	102	696	279	11	30	1	9	9	20	16	50	4	1440	48.3
α	94	32	47	26	134	590	134	146	19	40	52	53	20	39	14	1440	41.0
a	46	34	68	32	57	120	537	105	96	36	49	130	39	32	59	1440	37.3
ε	99	23	44	6	58	96	37	853	24	60	42	36	17	13	32	1440	59.2
e	45	36	50	50	45	21	36	50	770	63	75	33	75	19	72	1440	53.5
I	128	34	63	14	39	33	10	232	120	606	112	12	22	7	8	1440	42.1
i	27	173	252	9	11	9	1	13	35	105	783	1	11	3	7	1440	54.4
N_{resp}	1234	1177	2254	1106	1464	1245	806	1605	1153	1015	1284	389	479	387	218	15816	48.9

The monophthongs /ʌ/, /y/ and /o/ were often confused with the diphthongs not present in the stimulus set /ø/, /ø/ and /au/, respectively. Further, we found that the vowel /u/ was responded most frequently in all five conditions, followed by the vowels /ε/ and /ɔ/. Additionally, the results showed the largest improvements in vowel identification scores post-implantation with the implant switched on for the vowels /ε/, /y/ and /ʌ/ and the least improvement for the vowels /a/, /i/ and /u/; the latter are the corner points of the vowel triangle.

After transforming the confusion matrices into similarity matrices we applied the Kruskal analysis. For all five conditions these analyses were carried out in two dimensions, resulting in an acceptable solution with less than 10% stress. The results of the Kruskal analysis are shown in Fig. 2. In this figure we rotated the spatial representation of the vowels so as to obtain the highest correlation with the standard F_1F_2 representation.

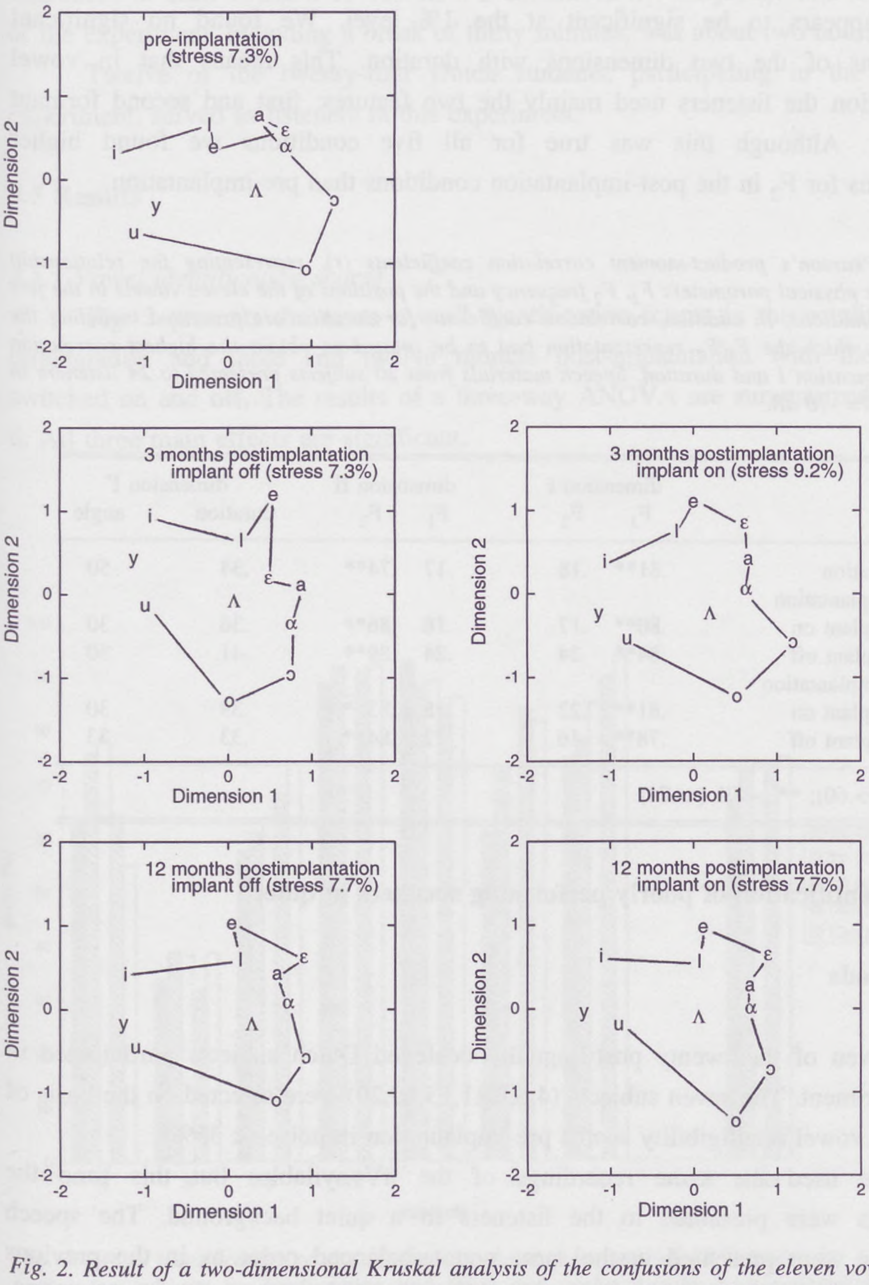

Fig. 2. Result of a two-dimensional Kruskal analysis of the confusions of the eleven vowels for all subjects. The results are presented for the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. All stimuli were presented in noise. Dimension I correlates with F_1 and dimension II with F_2.

Table 5 presents the correlation coefficients for the five conditions. In each condition, the correlation between dimension I and F_1 and between dimension II and F_2 appears to be significant at the 1% level. We found no significant correlations of the two dimensions with duration. This means that in vowel identification the listeners used mainly the two features: first and second formant frequency. Although this was true for all five conditions we found higher correlations for F_2 in the post-implantation conditions than pre-implantation.

Table 5. Pearson's product-moment correlation coefficients (r), representing the relationship between the physical parameters F_1, F_2 frequency and the positions of the eleven vowels in the five different conditions. In addition, correlation coefficients for duration are presented including the angle over which the F_1/F_2 representation had to be rotated to obtain the highest correlation between dimension I and duration. Speech materials from 20 subjects presented to 24 listeners in noise at S/N= -10 dB.

	dimension I		dimension II		dimension I′	
	F_1	F_2	F_1	F_2	duration	angle
pre-implantation	.81**	.18	.17	.74**	.34	50
3m post implantation						
implant on	.80**	.17	.16	.86**	.36	30
implant off	.84**	.24	.24	.89**	.41	50
12m post implantation						
implant on	.81**	.22	.18	.83**	.39	30
implant off	.78**	.16	.12	.84**	.33	33

* p<0.05 (r>.60); ** p<.01 (r>.74)

Vowel identification of poorly performing speakers in quiet

3.4 Methods

Seven of the twenty post-lingually deafened Dutch subjects participated in this experiment. The seven subjects (4,6,8,11,13,19,20) were selected on the basis of their low vowel intelligibility scores pre-implantation in noise (< 35%).

We used the same recordings of the hVt-syllables but this time the recordings were presented to the listeners in a quiet background. The speech conditions were presented in the same counterbalanced order as in the previous experiment and again the order of presentation of subjects and vowels randomized.

The number of vowel stimuli presented to each listener became 1155 (three utterances of each vowel x 11 vowels x 5 conditions x 7 subjects). The total length of the experiment, including a break of thirty minutes, was about two hours.

Twelve of the twenty-four Dutch students, participating in the previous experiment, served as listeners in this experiment.

3.5 Results

3.5.1 Vowel identification scores

Fig. 3 presents the mean overall identification scores in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. The results of a three-way ANOVA are summarized in Table 6. All three main effects are significant.

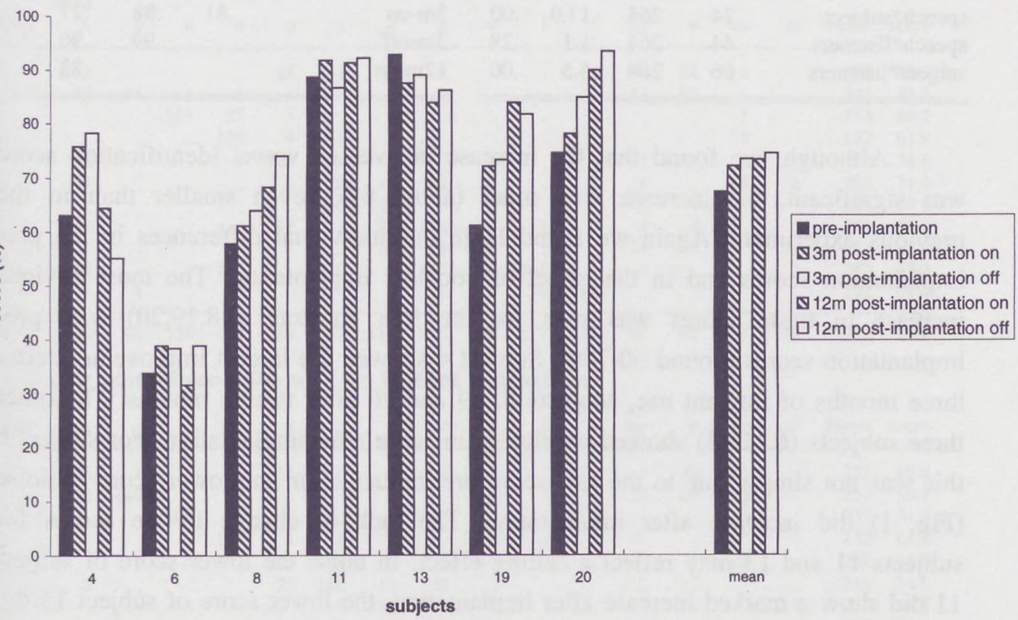

Fig. 3. Mean identification scores of vowels presented in quiet of 12 listeners for seven poorly performing subjects pre-implantation and three and twelve months post-implantation with the implant switched on and off.

Subsequent post-hoc tests (Tukey's HSD) for the factor speech-condition indicated a significant increase in the vowel identification scores at three months post-implantation with the implant switched on and off and twelve months post-implantation with the implant switched on and off as compared to the pre-implantation condition ($p<0.01$). No significant differences were found between all post-implantation conditions. We also noted a significant interaction between subjects and speech conditions and between subjects and listeners. We found no interaction between listeners and conditions.

Table 6. Results from a three-way ANOVA, giving factors, degrees of freedom (df), F-values and p-values. Subsequent post-hoc test results (Tukey's HSD) are given for the five different speech conditions pre-implantation (pre) and three (3m) and twelve months (12m) post-implantation with the implant switched on and off. Speech materials from 7 subjects presented to 12 listeners in quiet.

Factor	df_b	df_w	F-value	p
speech condition	4	44	19.9	.00
subjects	6	66	129.3	.00
listeners	11	264	48.8	.00
speech*subject	24	264	17.0	.00
speech*listeners	44	264	1.1	.28
subject*listeners	66	264	5.5	.00

post-hoc tests (p-values)	pre	3m on	3m off	12m on	12m off
pre		.00	.00	.00	.00
3m-on			.81	.88	.27
3m-off				.99	.90
12m-on					.83

Although, we found that the increase in average vowel identification score was significant, the increase was small (about 6%), even smaller than in the previous experiment. Again we found large interindividual differences in the pre-implantation scores and in the effect of cochlear implantation. The most obvious increase in these scores was seen for the four subjects (4,8,19,20) with pre-implantation scores around 60-70%. Subject 4 showed the largest improvement after three months of implant use, subjects 8, 19 and 20 after twelve months. The other three subjects (6,11,13) showed no change in score after implantation. For subject 6 this was not simply due to the low score pre-implantation; the lower score in noise (Fig. 1) did increase after implantation. The lack of change in the scores for subjects 11 and 13 may reflect a ceiling effect. In noise the lower score of subject 11 did show a marked increase after implantation, the lower score of subject 13 did not.

3.5.2 Multi Dimensional Scaling

Table 7 displays the vowel confusion matrices for the seven subjects and twelve listeners in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. When examining the pre-implantation matrix we noticed that the vowels /ʌ/, /y/, /u/, /ɔ/, /ɑ/, /e/, /I/ and /i/ are frequently confused with /ɔ/, /ʌ/, /o/, /ɑ/, /ɛ/, /a/, /ɛ/ and /I/, respectively. The inverse confusions were found less often, implying that F_1 was produced too high in frequency. We also found a diphthongization for the vowels /y/, /o/ and /e/ towards /ø/, /au/ and /ɛi/, respectively. Twelve months post-implantation with the implant switched on we found similar confusions for the vowels /ʌ/, /ɔ/, /ɛ/, /e/, /I/ and /i/ with /ɔ/, /ɑ/, /ɑ/, /a/, /ɛ/ and /I/, respectively.

Table 7. Vowel confusion matrices in the speech conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. Speech materials from 7 subjects presented to 12 listeners in quiet.

Pre-implantation

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	172	.	.	.	28	11	1	5	.	.	.	12	21	2	.	252	68.3
y	43	94	1	6	.	.	1	1	.	.	.	48	52	6	.	252	37.3
u	.	.	223	27	1	.	.	.	.	.	.	.	.	1	.	252	88.5
o	.	.	.	156	4	1	5	.	.	.	.	.	.	86	.	252	61.9
ɔ	12	.	.	7	188	30	5	.	.	.	.	1	1	8	.	252	74.6
ɑ	4	.	.	.	7	179	12	43	.	.	.	1	.	4	2	252	71.0
a	.	.	.	.	.	10	228	9	.	.	.	5	.	.	.	252	90.5
ɛ	49	.	.	.	11	3	35	136	4	2	.	3	9	.	.	252	54.0
e	1	.	.	.	.	2	20	13	156	.	.	23	4	.	33	252	61.9
I	4	.	.	.	.	2	6	47	26	161	3	1	.	.	2	252	63.9
i	1	4	.	.	.	.	.	1	17	54	175	.	.	.	.	252	69.4
N_{resp}	286	98	224	196	239	238	313	255	203	217	178	94	87	107	37	2772	67.4

3 months post-implantation with the implant switched on

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	176	1	1	1	14	19	5	3	.	.	.	4	15	13	.	252	69.8
y	8	149	.	3	.	.	2	.	.	.	.	27	60	3	.	252	59.1
u	.	.	205	39	2	.	.	.	.	.	.	.	.	6	.	252	81.3
o	.	.	.	154	1	1	3	.	.	.	.	6	.	87	.	252	61.1
ɔ	.	.	.	2	205	43	.	.	.	.	.	.	.	2	.	252	81.3
ɑ	3	.	.	.	25	188	14	20	.	.	.	2	.	.	.	252	74.6
a	.	.	.	.	.	6	223	11	1	.	.	7	.	.	4	252	88.5
ɛ	41	.	.	.	.	7	10	186	.	3	.	5	.	.	.	252	73.8
e	.	.	.	.	.	.	20	8	152	3	4	12	16	.	37	252	60.3
I	22	1	.	.	.	1	.	41	14	171	1	1	.	.	.	252	67.9
i	.	1	.	.	.	.	.	9	4	47	190	.	.	.	1	252	75.4
N_{resp}	250	152	206	199	247	265	277	278	171	224	195	64	91	111	42	2772	72.1

(Table 7 continued)

3 months post-implantation with the implant switched off

	resp																
stim	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	210	1	.	.	17	14	.	5	.	.	.	3	2	.	.	252	83.3
y	30	135	.	.	.	.	.	.	.	.	1	6	80	.	.	252	53.6
u	.	.	213	35	1	.	.	.	.	.	.	.	1	2	.	252	84.5
o	.	.	3	168	1	1	2	.	.	.	.	.	.	77	.	252	66.7
ɔ	1	.	.	2	207	40	.	.	.	.	.	.	.	2	.	252	82.1
ɑ	4	.	.	.	9	209	14	16	.	.	.	.	.	.	.	252	82.9
a	3	.	.	.	.	4	215	16	.	.	.	10	.	1	3	252	85.3
ɛ	45	.	.	.	.	16	6	170	.	6	.	6	2	.	1	252	67.5
e	.	.	.	.	.	.	9	17	165	2	.	14	10	.	35	252	65.5
I	12	.	.	.	.	6	4	50	5	145	29	1	.	.	.	252	57.5
i	.	.	.	.	.	.	.	.	10	42	199	.	1	.	.	252	79.0
N_{resp}	305	136	216	205	235	290	250	274	180	195	229	40	96	82	39	2772	73.4

12 months post-implantation with the implant switched on

	resp																
stim	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	199	.	1	4	30	6	.	.	.	.	.	.	7	5	.	252	79.0
y	17	155	29	.	.	.	.	.	.	.	.	5	46	.	.	252	61.5
u	.	.	210	31	8	.	.	.	.	.	.	.	.	3	.	252	83.3
o	.	1	.	160	2	.	3	.	.	.	.	.	.	86	.	252	63.5
ɔ	.	.	1	14	203	29	.	.	.	.	.	.	.	5	.	252	80.6
ɑ	3	.	.	.	2	201	37	8	.	.	.	.	.	1	.	252	79.8
a	1	.	.	.	.	24	222	2	.	.	.	2	.	1	.	252	88.1
ɛ	14	.	.	.	.	29	4	198	.	4	.	3	.	.	.	252	78.6
e	.	.	.	.	.	3	27	6	147	1	.	24	11	.	33	252	58.3
I	31	2	.	.	.	9	.	49	1	148	12	.	.	.	.	252	58.7
i	.	10	.	.	.	.	.	1	8	44	188	.	.	.	1	252	74.6
N_{resp}	265	168	241	209	245	301	293	264	156	197	200	34	64	101	34	2772	73.3

12 months post-implantation with the implant switched off

	resp																
stim	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	188	.	3	3	43	7	.	.	.	.	.	1	5	2	.	252	74.6
y	11	160	1	10	.	.	.	.	.	.	.	12	51	7	.	252	63.5
u	1	.	223	22	6	.	.	.	.	.	.	.	.	.	.	252	88.5
o	.	.	.	174	4	3	4	.	.	.	.	.	.	67	.	252	69.0
ɔ	.	.	1	1	202	46	.	.	.	.	.	.	.	2	.	252	80.2
ɑ	2	.	.	.	8	209	21	12	.	.	.	.	.	.	.	252	82.9
a	1	.	.	.	.	11	227	6	.	.	.	7	.	.	.	252	90.1
ɛ	10	.	.	.	4	21	5	199	1	12	.	.	.	.	.	252	79.0
e	.	.	.	.	.	1	26	8	144	.	.	38	6	.	29	252	57.1
I	43	1	.	.	.	9	1	53	5	139	1	.	.	.	.	252	55.2
i	5	5	.	.	.	1	.	.	8	30	202	.	1	.	.	252	80.2
N_{resp}	261	166	228	210	267	308	284	278	158	181	203	58	63	78	29	2772	74.6

Again, these results suggested that F_1 was produced too high in frequency. Diphthongization was present for the vowels /y/, /o/ and /e/ towards /ø/, /au/ and /ɛi/. Further, the matrices show the largest improvements for the vowels /y/, /ɛ/ and

/ʌ/ at twelve months post-implantation with the implant on as compared to the pre-implantation condition. This result is similar to that found in the previous vowel identification experiment in noise. Again, the corner point vowels /a/,/i/ and /u/ showed smaller effects.

The matrices of Table 7 were transformed to similarity matrices that were submitted to Kruskal analysis in two dimensions. The results of these analyses are depicted in Fig. 4. In all cases the stress values were less than 11%, implying that there was no need to look for a third dimension to adequately represent the results. In Fig. 4 we rotated the results to the highest correlation with the standard F_1F_2 representation. Table 8 presents the correlation coefficients (r) for the five conditions. Pre-implantation the correlation between dimension I and F_1 and between dimension II and F_2 was significant at the 1% level.

Table 8. Experiment IIa: Pearson's product-moment correlation coefficients (r), representing the relationship between the physical parameters F_1, F_2 frequency and the positions of the eleven vowels in the five different conditions. In addition, correlation coefficients for duration are presented including the angle over which the F_1F_2 representation had to be rotated to obtain the highest correlation between dimension I and duration. Speech materials from 7 subjects presented to 12 listeners in quiet.

	dimension I		dimension II		dimension I′	
	F_1	F_2	F_1	F_2	duration	angle
pre-implantation	.75**	.34	.07	.85**	.79**	5
3m post implantation						
implant on	.66*	.03	.05	.89**	.34	-15
implant off	.25	.41	.11	.93**	.68*	0
12m post implantation						
implant on	.75**	.12	.10	.92**	.75**	-10
implant off	.77**	.01	.03	.93**	.55	-20

* $p<0.05$ (r>.60); ** $p<.01$ (r>.74)

Also, pre-implantation we noted a significant correlation between dimension I and duration. The highest correlations between dimension I and duration (r=.79) were found when the F_1F_2 presentation was rotated over 5 degrees (Table 8). At three months post-implantation we found a strong relation between the F_2 and dimension II both with the implant switched on and switched off. The relation between dimension I and the F_1 was rather weak. However, we did find a significant

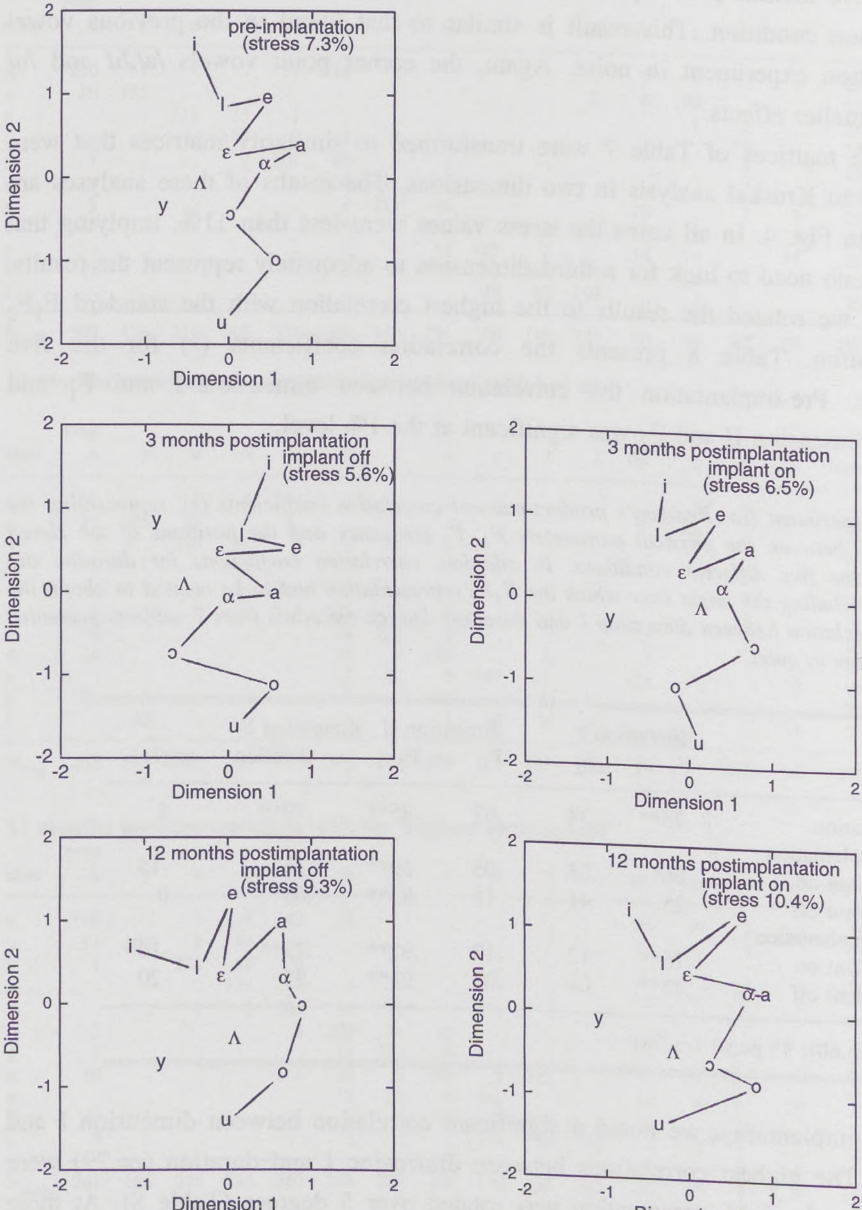

Fig. 4. Result of a two-dimensional Kruskal analysis of the confusions of the eleven vowels for the seven poorly performing subjects. The results are presented for the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. All stimuli were presented in quiet.

correlation between dimension I and vowel duration in the implant switched off condition ($p<0.05$). At twelve months post-implantation with the implant switched on we noted both a significant correlation between the dimension I and F_1 and dimension II and F_2. With the implant switched on we also noticed a significant correlation with duration ($p<0.01$). The highest correlation was found when the F_1F_2 was rotated over -10 degrees.

It is interesting to find different outcomes of the Kruskal analyses for the twenty subjects in the noise condition and the seven subjects in the quiet condition. In order to find out whether these differences are the result of the different subject groups or an effect of the presented noise we also computed the matrices for the seven subjects in the noise condition. The results are presented in Table 9.

Table 9. Vowel confusion matrices in the speech conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. Speech materials from 7 subjects presented to 24 listeners in noise at S/N=-10 dB.

Pre-implantation

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	ɪ	i	œy	ø	au	ɛi	Npres	score
ʌ	69	6	55	58	117	45	7	30	17	9	8	35	31	12	5	504	13.7
y	42	90	106	55	40	3	10	10	13	9	28	20	52	19	7	504	17.9
u	40	58	235	44	29	6	2	5	12	10	26	4	22	7	4	504	46.6
o	18	13	29	161	64	33	15	14	14	6	2	25	27	73	10	504	31.9
ɔ	33	4	12	65	189	95	11	27	2	3	2	10	13	37	1	504	37.5
ɑ	27	24	45	19	51	109	35	72	20	17	14	28	15	15	13	504	21.6
a	23	16	41	33	45	59	78	53	25	22	17	26	25	29	12	504	15.5
ɛ	48	28	35	33	78	52	40	67	18	7	16	29	24	19	10	504	13.3
e	40	23	52	56	46	26	29	42	66	19	14	20	35	16	13	504	13.1
ɪ	78	20	58	12	30	28	12	71	71	42	27	7	35	6	7	504	8.3
i	22	74	161	11	16	11	.	7	37	26	107	4	16	6	6	504	21.2
N_{resp}	440	356	829	547	705	467	239	398	295	170	261	208	302	239	88	5544	21.9

3 months post-implantation with the implant switched on

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	ɪ	i	œy	ø	au	ɛi	Npres	score
ʌ	92	19	81	54	56	58	6	26	6	13	11	22	42	14	4	504	18.3
y	22	137	141	24	8	3	17	4	9	7	35	26	53	13	5	504	27.2
u	16	41	271	47	38	11	9	9	4	12	21	1	11	12	1	504	53.8
o	16	6	35	228	59	31	15	5	13	6	3	15	19	51	2	504	45.2
ɔ	27	6	22	62	207	109	12	16	4	1	.	8	7	23	.	504	41.1
ɑ	30	14	47	30	80	130	40	36	13	14	27	13	10	16	4	504	25.8
a	23	19	36	23	27	55	98	44	30	14	25	47	22	27	14	504	19.4
ɛ	58	14	25	22	20	27	27	203	8	22	28	23	12	6	9	504	40.3
e	22	17	27	41	14	25	21	39	139	22	17	29	31	14	46	504	27.6
ɪ	49	21	53	6	22	10	2	96	55	144	32	.	12	.	2	504	28.6
i	24	53	96	1	8	5	3	25	12	43	225	.	6	1	2	504	44.6
N_{resp}	379	347	834	538	539	464	250	503	293	298	424	184	225	177	89	5544	33.8

(Table 9 continued)

3 months post-implantation with the implant switched off

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	125	30	69	47	68	47	11	21	12	4	6	14	41	7	2	504	24.8
y	23	117	156	21	6	4	6	3	9	5	28	21	98	6	1	504	23.2
u	24	39	289	37	38	12	5	11	6	8	12	7	6	8	2	504	57.3
o	9	2	27	228	77	31	15	10	9	.	1	14	22	55	4	504	45.2
ɔ	11	.	10	66	237	121	6	27	1	2	.	7	5	20	1	504	45.0
ɑ	30	12	24	20	68	193	40	33	10	6	3	24	7	32	2	504	38.3
a	31	18	19	31	34	78	91	44	30	15	18	44	17	19	15	504	18.1
ɛ	64	16	35	19	39	54	19	185	11	11	7	16	10	11	7	504	36.7
e	14	11	17	36	19	5	12	43	142	56	17	22	38	12	60	504	28.2
I	62	18	51	10	20	30	8	58	22	133	69	2	14	3	3	504	26.4
i	9	81	114	3	1	8	3	17	30	33	194	2	6	1	2	504	38.5
N_{resp}	402	344	811	518	597	583	216	452	282	273	355	173	265	174	99	5544	34.7

12 months post-implantation with the implant switched on

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	95	23	100	52	102	23	2	17	11	15	12	10	30	8	4	504	18.8
y	15	93	247	27	8	2	3	1	19	10	27	5	39	3	5	504	18.5
u	31	30	254	56	39	8	2	7	11	10	30	2	18	1	5	504	50.4
o	12	6	42	210	58	20	14	5	25	1	2	17	37	45	10	504	41.7
ɔ	26	15	50	65	208	71	3	17	3	1	14	13	7	10	1	504	41.3
ɑ	37	16	76	8	77	122	24	44	9	21	24	27	13	6	.	504	24.2
a	29	18	53	32	39	62	65	44	24	11	24	40	35	21	7	504	12.9
ɛ	89	15	42	5	45	65	21	118	11	18	30	23	10	7	5	504	23.4
e	29	26	64	46	26	23	19	22	66	12	45	34	65	13	14	504	13.1
I	79	31	82	3	44	34	9	45	34	67	41	9	19	3	4	504	13.3
i	23	85	166	3	11	10	.	5	20	22	143	2	11	1	2	504	28.4
N_{resp}	465	358	1176	507	657	440	162	325	233	188	392	182	284	118	57	5544	26.0

12 months post-implantation with the implant switched off

stim \ resp	ʌ	y	u	o	ɔ	ɑ	a	ɛ	e	I	i	œy	ø	au	ɛi	Npres	score
ʌ	119	17	82	62	108	30	4	16	7	9	3	11	23	12	1	504	23.6
y	14	142	177	36	6	8	5	4	14	10	39	10	24	14	1	504	28.2
u	22	47	307	24	23	6	1	5	3	5	32	2	20	6	1	504	60.9
o	14	4	47	168	69	40	21	7	16	4	4	24	30	50	6	504	33.3
ɔ	28	9	56	47	200	96	7	10	1	1	8	9	3	26	3	504	39.7
ɑ	34	22	39	22	62	175	38	39	4	13	20	12	10	8	6	504	34.7
a	27	20	42	17	35	68	83	39	28	16	26	47	24	19	13	504	16.5
ɛ	77	22	44	1	47	78	26	109	7	13	29	25	10	10	6	504	21.6
e	37	30	45	41	40	19	28	31	83	26	20	29	51	14	10	504	16.5
I	91	25	62	14	34	32	9	76	18	65	37	12	20	7	2	504	12.9
i	17	94	187	8	7	6	1	9	8	21	135	2	5	2	2	504	26.8
N_{resp}	480	432	1088	440	631	558	223	345	189	183	353	183	220	168	51	5544	28.6

These matrices show the largest improvement at three months post-implantation. In contrast the largest improvement in the quiet condition was seen at twelve months post-implantation. The vowels /ʌ/, /y/, /ɔ/, /ɑ/, /a/, /I/ and /i/ were often confused with /ɔ,u/, /u/, /ɑ/, /ɛ/, /ɑ/, /ʌ,ɛ/ and /u/, respectively. Obviously, the vowel /u/ was responded the most in all five speech conditions. In addition, we found the largest improvements in vowel identification scores for the vowels /ɛ/, /I/ and /i/. Again, Kruskal analyses were performed. The results are presented in Fig. 5. In addition, Table 10 presents the correlations between the perceptual dimensions and the physical variables. The correlation between dimension I and F_1 is significant in all conditions. The correlation between dimension II and F_2 is significant in all conditions except one, the condition twelve months post-implantation with the implant switched on in which the correlation value just failed to reach the significance level of 5%. However, at twelve months post-implantation with the implant switched on we found a significant correlation between dimension I and duration when F_1/F_2 was rotated over -115 degrees, implying a correlation between dimension II and duration. The results of Fig. 5 are more similar to those of Fig. 2 than to those of Fig. 4 suggesting that the difference between the results of Fig. 4 and Fig. 2 should be attributed to the measurement condition (quiet versus noise, respectively) and not to the selection of the seven subjects.

Table 10. Experiment IIb: Pearson's product-moment correlation coefficients (r), representing the relationship between the physical parameters F_1, F_2 frequency and the positions of the eleven vowels in the five different conditions. In addition, correlation coefficients for duration are presented including the angle over which the F_1F_2 representation had to be rotated to obtain the highest correlation between dimension I and duration. Speech materials from 7 subjects presented to 24 listeners in noise.

	dimension I		dimension II		dimension I′	
	F_1	F_2	F_1	F_2	duration	angle
pre-implantation	.82**	.19	.33	.61*	.37	100
3m post implantation						
implant on	.66*	.18	.17	.84**	.48	-45
implant off	.76**	.28	.30	.86**	.41	0
12m post implantation						
implant on	.83**	.32	.30	.57	.61*	-115
implant off	.84**	.23	.28	.60*	.43	50

* p<0.05 (*r*>.60); ** p<.01 (*r*>.74)

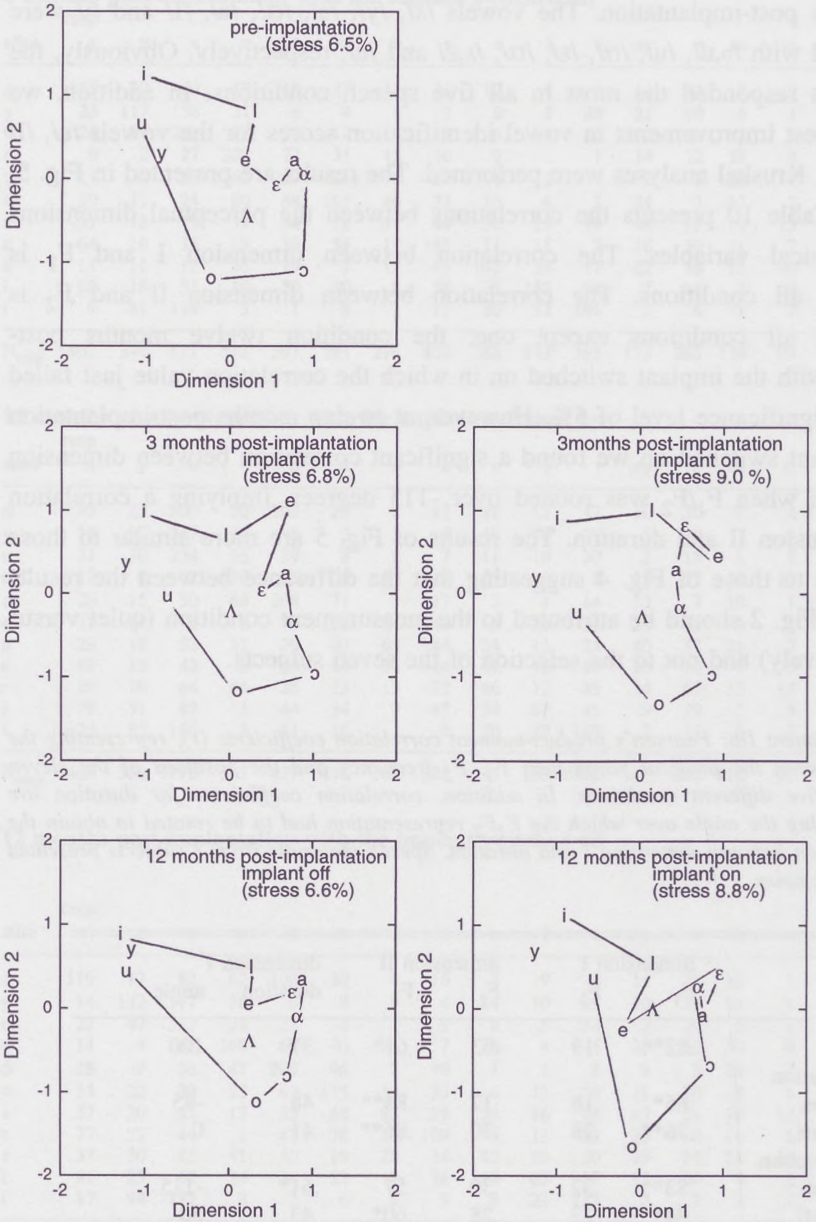

Fig. 5. Result of a two-dimensional Kruskal analysis of the confusions of the eleven vowels for the seven poorly performing subjects. The results are presented for the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. All stimuli were presented in noise.

3.6 Discussion

This study shows that vowel intelligibility measured in noise increases after implantation in post-lingually deafened adults. Thus, older deaf subjects are able to improve their speech production. Dawson *et al.* (1995) showed improvements of speech intelligibility after cochlear implantation in children, adolescents and pre-lingually deafened adults. However, they did not find significant changes in vowel performance, although the p-value only just failed to reach significance.

We found the highest identification scores measured in noise at three months post-implantation with the implant switched on. Although, at twelve months post-implantation both with the implant switched on and off these scores are still significantly higher than pre-implantation we noted a significant decrease in the vowel identification scores at twelve months after implantation as compared to the three months post-implantation condition with the implant switched on. This could not be accounted for by a decrease in auditory perception of the subjects. In most subjects, we even found an increase in CVC (consonant-vowel-consonant) perception at twelve months post-implantation as compared to three months post-implantation. After an initial period of intense attention for their own speech production, a period may follow in which the perception of ones own speech is taken for granted, resulting in less attention and as a possible consequence less accurate vowel production.

Switching off the implant at three months post-implantation resulted in a significant decrease in the identification score as compared to the implant on condition. However, twelve months post-implantation we noted no difference between the respective switched on and off conditions. Also, these results suggest that at the beginning of the rehabilitation period the implant users pay more attention to the auditory information provided by the implant resulting in improved vowel production with the implant switched on as compared to the switched-off condition. However, we should realize that the differences between the mean vowel identification scores across all subjects in the five conditions are small. This means that reaching the significance levels is partially based on the large number of implantees and listeners included in this study.

In examining the five matrices we found large biased confusions for the vowels /ʌ/, /y/, /ɔ/, /ɑ/, /I/ and /i/ with /ɔ/, /u/, /ɑ/, /ɛ/, /ɛ/ and /u/, respectively. In addition, the vowel /u/ was responded the most. This implies that F_2 was often produced too low in frequency. Largest improvements after implantation were found for the vowels /y/, /ɛ/ and /ʌ/ and the smallest effects for the corner point vowels /a/, /i/ and /u/. This last result is in line with that of Svirsky and Tobey (1991), who found no significant changes in the point vowels when switching on the implant after approximately 12 hours of non-use.

In all five noise conditions we found that the correlations between dimension I and II of the Kruskal outcome and the first and second formant frequencies were statistically significant although, post-implantation, the correlations were higher for dimension II and F_2. The decrease in the number of vowel confusions when using the implant might well be related to the changes in F_1 and F_2 frequency after implantation reported previously (Langereis *et al.*, 1997): an increase in the range of frequencies covered by the F_1 and F_2 of the eleven vowels; a decrease in the deviation of F_1 and F_2 from the norm frequencies as measured by Pols (1977) for male speakers and by Van Nierop *et al.* (1973) for female speakers; a decrease in the variability in both formant frequencies within individuals and an increase in the clustering rate, defined as the ratio of the between-vowel variance of F_1 and F_2 and the within-vowel variance of three tokens of the same vowel within individuals. This increase in clustering rate implies an improvement in the ability to make phonological contrasts between vowels. The previous study also showed that post-lingually deafened subjects improve their vowel production after implantation. In order to quantify the relation between the two studies we calculated the coefficient of the correlation between the intelligibility scores of the present study and the objective measurements of the previous one. Table 11 presents the correlation coefficients for the five conditions across all twenty subjects. We found the highest correlations between the vowel intelligibility scores and the frequency range of F_2 ($p<0.01$ in all conditions), followed by correlations with the measurements on the deviations of F_2 and F_1 from the norm values. Table 11 shows weaker correlations between the vowel intelligibility score and the clustering rate for both formants, the variability in both formant frequencies and the frequency range of F_1. In summary, the comparison between the two studies shows that lower intelligibility scores are mainly due to a smaller F_2 range. Before, we noticed already a bias in the confusion matrices toward /u/ responses which was interpreted in terms of F_2 often produced too low in frequency. This is in line with the present conclusion. The previous study showed that improvement in vowel production after implantation is mainly found in an extension of the F_1 range rather than the F_2 range. This suggests that more attention should be paid to improving F_2 production in order to improve vowel intelligibility of the implanted subjects.

Table 11. Pearson product-moment correlation coefficients for the relationship between vowel intelligibility scores of twenty subjects in noise (this study) and objective measurements on vowel quality (Langereis et al. 1997): the range of frequencies covered by the F_1 and F_2 of the eleven vowels, the deviation of F_1 and F_2 from the norm frequencies as measured by Pols (1977) for male speakers and by Van Nierop (1973) for female speakers, the variability in both formant frequencies and the clustering rate for both formant frequencies. Correlation coefficients are presented in the conditions pre-implantation and three (3m) and twelve months (12m) post-implantation with the implant switched on and off.

	pre	3m on	3m off	12m on	12m off
Frequency range F_1	0.48*	0.37	0.33	0.37	0.31
Frequency range F_2	0.62**	0.69**	0.72**	0.63**	0.66**
F_1-deviations from norm	0.44	-0.44	-0.63**	-0.41	-0.49*
F_2-deviations from norm	-0.46	-0.58**	-0.53	-0.37	-0.61**
Variability in F_1	-0.16	-0.30	-0.42	-0.23	-0.39
Variability in F_2	0.05	-0.26	-0.03	-0.40	-0.55*
Clustering rate F_1	0.10	0.62**	0.28	0.38	0.43
Clustering rate F_2	0.31	0.41	0.14	0.47*	0.65**

* $p<0.05$; ** $p<0.01$

Although the overall results showed an improvement in vowel identification scores a number of subjects showed little or no improvement; there was large variability between individual subjects in the effect of cochlear implantation. This also holds for the pre-implantation data. In order to examine a possible influence of the masking noise on the outcomes of the experiment we added the experiment in quiet for a subgroup of the most poorly performing speakers who, without masking, would give intelligibility scores below 100%. Post-implantation we found a significant increase in the vowel identification scores versus pre-implantation. However, the increase in mean vowel identification score for the subgroup in quiet was only 6%, even smaller than the overall result in noise (9%). In noise, the largest increase for the subgroup was 12%. This shows that the small increase of 6% in quiet may be related to the measurement condition (quiet versus noise condition, respectively) and not to the subgroup per se. This is also implied by the finding that for the subgroup in noise the highest intelligibility scores were found at three months post-implantation as was found for the overall result collected in the noise condition but was not found for the subgroup in the quiet condition.

The vowel confusions found in the quiet condition for the seven poorly performing subjects suggest that F_1 was produced too high in frequency by these subjects. In comparing the pre-implantation ranges of F_1 for the poorly performing with those for the 13 better performing subjects we found that the ranges of F_1 for the poorly performing subjects were non-significantly smaller (p=0.07). However, when examining the individual pre-implantation F_1 values for the poorly performing subjects we found that larger F_1 ranges in these seven subjects were usually the result of the position of only one or two vowels; i.e. /i/ or /y/ were produced with extreme low F_1 values as compared to the F_1 values of the other vowels. As a consequence these other vowels still covered a small range of F_1. These results correspond to the outcome of the vowel confusions of the present study implying vowels to be produced with too high F_1 values. In contrast to the overall result collected in the noise condition we found relatively less /u/ responses and more /ʌ/, /a/ and /ɛ/ responses in the quiet condition. However, the vowel confusions for the subgroup in noise again show an obvious tendency for vowels with higher F_2 to be confused with vowels with lower F_2 and a large number of /u/ responses, in accordance with the overall result in the noise condition. This suggests that in noise some F_2 information is masked, shifting the cues for vowel identification to F_1 information, which resulted in more /u/ responses.

Finally, the Kruskal analysis in the quiet condition for the seven poorly performing speakers showed some marked differences with respect to the Kruskal analysis for all subjects in the noise condition. Pre-implantation, the correlation between dimension I and the parameters F_1 and duration and between dimension II and F_2 were statistically significant. At three months post-implantation we found high correlations between the dimension II and F_2, however the correlation between dimension I and F_1 was rather weak. In the implant switched off condition we found a significant correlation between dimension I and duration. Interestingly, at twelve months post-implantation F_1 became more important again, resulting in both first and second formant frequency and vowel duration to be used in vowel identification. These results are in line with the objective measurements of the previous study showing an increase of the F_1 range after implantation. The results for the subgroup collected in noise rather than in quiet show that dimension I correlates significantly with F_1 in all conditions. The correlation between dimension II and F_2 is statistically significant in all conditions, except the condition twelve months post-implantation with the implant switched on. Thus, these results were very similar to those for the whole group in noise and dissimilar to those for the same subgroup in quiet. This implies a considerable influence of the masking noise on these results.

In describing the results of the vowel identification experiments we should realize that variables other than the first and second formant frequencies and duration may have played a part in the identification of the vowels: e.g. the amplitude ratio of F_1/F_2, the third formant; co-articulation effects, and voice characteristics. For instance, in slight hoarseness the regular harmonic components, especially the second and third formants, are mixed with a noise component. (Yanagihara, 1967). This could influence vowel perception in noise more so than in quiet resulting in relatively lower scores in the noise condition. A relatively low score was found in subject 20, who spoke hoarsely at twelve months post-implantation.

Table 12. Pearson product-moment correlation coefficients (r) for the relationship between vowel intelligibility scores of seven poorly performing subjects in quiet (this study) and objective measurements on vowel quality (Langereis et al. 1997): the range of frequencies covered by the F_1 and F_2 of the eleven vowels, the deviation of F_1 and F_2 from the norm frequencies as measured by Pols (1977) for male speakers and by Van Nierop (1973) for female speakers, the variability in both formant frequencies and the clustering rate for both formant frequencies. Correlation coefficients are presented in the conditions pre-implantation and three (3m) and twelve months (12m) post-implantation with the implant switched on and off.

	pre	3m on	3m off	12m on	12m off
Frequency range F_1	0.54	0.37	0.21	0.56	0.56
Frequency range F_2	0.60	0.79*	0.84*	0.80*	0.84*
F_1-deviations from norm	0.50	0.51	-0.25	0.29	0.10
F_2-deviations from norm	-0.72	-0.85*	-0.81*	-0.85*	-0.85*
Variability in F_1	-0.67	-0.08	-0.08	-0.59	0.70
Variability in F_2	0.70	-0.40	-0.25	-0.80*	-0.73
Clustering rate F_1	0.85*	0.34	0.23	0.51	0.28
Clustering rate F_2	0.94**	0.39	0.62	0.63	0.66

* $p<0.05$; ** $p<0.01$

Also, for the quiet condition we calculated the coefficient of the correlation between the intelligibility scores of the present study and the results of the objective measurements of the previous one. These coefficients for the subgroup of seven subjects are presented in Table 12. We found the strongest correlations between the intelligibility scores and both the frequency range of F_2 and the deviations of the F_2 from the norm values ($p<0.05$ in all conditions except pre-implantation), followed by correlations with the clustering rate and the variability in F_2. Further, Table 12 shows weaker correlations between the vowel intelligibility scores and F_1 measurements. Thus, similar to the results in the noise condition we find the strongest correlations with F_2-measurements, implying that the vowel intelligibility scores of the subgroup are primarily determined by the position of F_2 frequencies.

3.7 Conclusions

In summary, our study shows that cochlear implantation with a Nucleus 22 implant increases vowel intelligibility in noise measured for a large group of subjects in background noise. Twelve months after implantation listeners used both F_1 and F_2 to identify vowels. This also holds for a subgroup of speakers who were performing poorly pre-implantation. However, for this subgroup we found that when these vowels were presented in a quiet background listeners also used duration in the identification of the vowels. In comparing the results of the subgroup of seven poor speakers in the noise and in the quiet condition we found the results of the subgroup in noise to be more similar to the result for the whole group in noise. This suggests that the differences between the overall result in noise and the results of the subgroup in quiet should mainly be attributed to the noise and not to aspects of poor speech productions in the subgroup.

The second issue we addressed in this study was the relation between the intelligibility scores and objective measurements of vowel quality of the previous study. We found the strongest correlations between vowel identification scores and the frequency range of F_2 and the deviation of F_2 to the norm values in vowel production. This shows that the vowel intelligibility scores are mainly determined by the position of the second formant frequencies.

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CHAPTER 4

EFFECT OF COCHLEAR IMPLANTATION ON *VOICE FUNDAMENTAL FREQUENCY* IN POST-LINGUALLY *DEAFENED ADULTS*

Effect of cochlear implantation on voice fundamental frequency in post-lingually deafened adults

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Abstract

The present study addresses the effect of cochlear implantation on the voice fundamental frequency at which twenty post-lingually deafened Dutch subjects utter speech materials. All subjects received the Nucleus 22 cochlear implant (3 WSP and 17 MSP processors). Speech recordings were made pre-implantation and three and twelve months post-implantation with the implant switched on and off. The fundamental frequency (f_0) was sampled while reading a text.

The pre-implantation results show that in some subjects f_0 was too high compared to the range in f_0 of normal-hearing subjects. Post-implantation, with the implant switched on, we found that the abnormally high f_0 values pre-implantation, changed toward the norm values.

Also, post-implantation we found that the range over which f_0 varied within one subject while reading the text, the f_0 sway, decreased for most subjects who pre-implantation had their f_0 sway outside the normal range; the normal range being defined as the interval between the mean plus/minus one standard deviation of the f_0 sway found for normal-hearing subjects.

Voice fundamental frequency of post-lingually deafened adults is characterized by large interindividual variability in the pre-implantation f_0 values. This large interindividual variability is found also in the effect of cochlear implantation on f_0.

4.1 Introduction

In the literature on speech production of post-lingually deafened adults we find different results as to the effect of post-lingual deafness on voice fundamental frequency. In 21 profoundly deaf male subjects Leder *et al.* (1987) measured values for voice fundamental frequency (f_0) higher than those in normal-hearing subjects. Using listeners' perceptual judgments, Leder and Spitzer (1990) found deviations in pitch in post-lingually deafened male subjects. However, Waldstein (1990) reported no significant differences in mean f_0 between seven post-lingually deafened subjects (two males and five females) and normal-hearing speakers. Additionally, Waldstein found that it was impossible to distinguish the deafened speakers from the hearing speakers on the basis of the standard deviation of f_0; defined as the f_0 sway in this study. This last finding contrasts with the results of the study of Lane and Webster (1991), who found greater than normal fluctuations of f_0 within sentences in three profoundly deafened subjects (one male and two females). Plant and Hammarberg (1983), however, noted a constricted f_0 range in two post-lingually deafened subjects (one male and one female).

If deviations in fundamental frequency and its sway are present in post-lingually deafened subjects, what would be the effect on f_0, when auditory feedback is partially restored by a cochlear implant? McKay and McDermott (1993) showed that Nucleus cochlear implants users could identify intonation patterns well above chance level. Thus, the perception of one's own voice might influence the f_0 at which cochlear implant users speak.
Kirk and Edgerton (1983) examined the effect of implantation of a single-channel cochlear implant in four post-lingually deafened subjects (two males and two females). With the implant switched on they found for the male subjects when reading a standard text lower f_0 values than in the implant switched-off condition. For both male subjects the f_0 values were closer to those obtained for the male control speakers. Moreover, the male subjects demonstrated less variability in f_0 in the condition with the implant switched on as compared to the switched-off condition. However, even in the switched-on condition, they showed more variability of f_0 than the male control speakers. For the female subjects f_0 was higher when the implant was switched on. As for the male subjects, f_0 values moved into the direction of the f_0 values of the female control speakers. The female subjects displayed increased variability of f_0 with the implant switched on, resulting in f_0 variations closer to those of the control speakers. Also, Plant and Oster (1986) found a higher mean f_0 and a slight increase in the standard deviation of f_0 in a female subject two years after implantation with a single-channel cochlear implant. After implantation with the Vienna Cochlear Prosthesis, Oster (1987) found a considerable lowering in mean f_0 for both a male and a female post-lingually deafened subject. For both subjects the lowering of f_0 resulted in a value more comparable to those found for normal-hearing speakers of the same age and sex.

Post-implantation a decrease in f_0 sway was noted in the two subjects. Especially for the male subject this resulted in improved intonation. Read (1989) evaluated speech production in 30 single-channel implant users. 43% of the subjects showed considerable improvement in intonation and pitch control. Tartter (1989) studied the effect of cochlear implantation of the Nucleus multi-channel implant on f_0 in a post-lingually deafened teenager. Post-implantation, f_0 rose 25-30 Hz, which was an improvement. Listeners judged the post-implant recordings as having better intonation than earlier ones. With the Ineraid implant Svirsky *et al.* (1992) noticed in three post-lingually deafened adults that switching off the implant for a 24-hour period resulted in a rise of f_0 toward abnormally high values when uttering vowels. The effect of switching the implant on after the 24-hour period of auditory deprivation was a lowering of the fundamental frequency of 10 - 32 Hz.

In summary, the limited literature is inconclusive as to the question of how f_0 changes after cochlear implantation although there seems to be a trend toward the mean f_0 and sway found for control, normal-hearing speakers. The post-lingually deafened adults form a heterogenous group. In the present study, therefore, we evaluated f_0 in a large group of twenty post-lingually deafened subjects before and after implantation with the Nucleus multichannel cochlear implant. Also, we evaluated the short-term effects of switching the implant on and off.

4.2 Methods

4.2.1 Subjects

Recordings were made of twenty post-lingually deafened Dutch subjects (twelve females and eight males). All subjects received the Nucleus 22 cochlear implant (3 WSP and 17 MSP processors). After implantation they only received auditory training. No explicit speech therapy was given. Additional information about the subjects is given in Table 1.

4.2.2 Material

The speech material consisted of a text (commonly used in speech evaluation of cochlear implant candidates in the Netherlands), which was read in about 40 seconds. Recordings were made pre-implantation and three and twelve months post-implantation with the implant switched on and off. In the off-condition the subjects did not use their implant during the half-hour period prior to the measurements.

Table 1. Subject and implant characteristics ordered according to gender and duration of deafness.

	gender	age	etiology	duration of deafness in years	number of active electrodes 3m	12m	mean dynamic range (dB) 3m	12m	stimulus strategy 3m	12m	CVC phoneme score (%) 3m	12m
1	m	29	meningitis	1	22	21	8.3	13.2	$f_0/F_1/F_2$	$f_0/F_1/F_2$	54.0	47.6
2	m	64	progressive	1	19	18	7.0	10.2	mpeak	mpeak	55.9	40.7
3	m	51	otosclerosis	3	22	22	5.3	4.7	mpeak	mpeak	6.9	27.9
4	m	28	meningitis	9	20	20	3.3	4.7	mpeak	mpeak	19.0	28.5
5	m	29	meningitis	12	22	22	8.0	8.0	mpeak	mpeak	27.4	37.5
6	m	32	meningitis	22	11	11	9.9	9.5	$f_0/F_1/F_2$	f_0/F_2	11.3	9.2
7	m	33	meningitis	24	22	22	10.3	13.9	$f_0/F_1/F_2$	$f_0/F_1/F_2$	4.3	27.6
8	m	51	meningitis	40	22	22	4.9	5.6	mpeak	mpeak	0.0	21.5
9	f	65	otosclerosis	2	16	16	4.9	4.3	mpeak	mpeak	13.0	23.8
10	f	52	meningitis	3	20	15	7.6	7.4	mpeak	mpeak	28.5	28.8
11	f	40	otitis	4	21	16	4.4	1.2	mpeak	mpeak	13.2	27.1
12	f	37	progressive	5	18	18	2.8	2.1	mpeak	mpeak	32.5	35.9
13	f	33	unknown	5	18	14	5.3	3.5	mpeak	$f_0/F_1/F_2$	2.7	3.5
14	f	49	otosclerosis	6	20	20	3.5	3.5	mpeak	mpeak	35.1	30.0
15	f	54	unknown	7	22	22	4.3	4.3	mpeak	mpeak	45.8	43.1
16	f	68	unknown	8	22	20	4.5	2.8	mpeak	$f_0/F_1/F_2$	22.6	22.3
17	f	40	progressive	11	20	20	3.9	3.0	mpeak	mpeak	36.0	41.5
18	f	43	otitis	39	17	14	0.8	1.2	mpeak	mpeak	5.5	10.4
19	f	56	unknown	41	16	12	1.6	2.8	mpeak	mpeak	9.4	13.0
20	f	57	meningitis	47	20	20	2.3	3.2	mpeak	mpeak	2.7	11.8

All subjects have an MSP, except for subject 1,6 and 7, who have an WSP processor.

The order of the on- and off- conditions was counterbalanced across all subjects. The subject was sitting with the microphone (Sennheiser, MD 421 HL) at a distance of 30 cm. Analogue recordings were made with a Revox A77 tape recorder (bandwidth 20 kHz) in a sound-treated room.

4.2.3 Speech analysis

The speech recordings were digitized (10 kHz sampling rate, 14 bit resolution) and analyzed applying Entropic software (Entropic Speech Processing System, Entropic Research Laboratory, Inc.) running on a SUN workstation. f_0 values were estimated every 10 ms using a 12th order LPC analysis with a 50-ms Hamming window.

4.3 Results

4.3.1 Individual mean fundamental frequency

In Fig. 1 the mean fundamental frequency value during the 40 s text is presented for each of the twelve female subjects in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. ANOVA (CSS Statistica) of these individual mean values revealed a significant effect of implant use on f_0 [$F(4,44)=2.54$, $p \leq 0.05$). Subsequent posthoc analysis (Tukey's Honestly Significant Difference test as implemented in CSS Statistica) demonstrated a significant decrease of f_0 relative to pre-implantation for only the twelve months post-implantation condition with the implant switched on ($p<0.05$).

In order to find out whether this decrease was a change toward the normal mean we compared the present results to the group mean of 30 Dutch female normal-hearing speakers as measured by Tielen (1992) applying a similar f_0 measurement technique. Fig. 2 displays, per female subject, the individual mean fundamental frequency for the pre-implantation condition and the two post-implantation conditions with the implant switched on together with the normal group mean and this group mean plus and minus one standard deviation for normal-hearing female speakers. Pre-implantation, 66% of the f_0 data fell within the normal range of f_0 as compared to 92% at three and twelve months post-implantation with the implant switched on. The f_0 values outside the normal range pre-implantation were all too high.

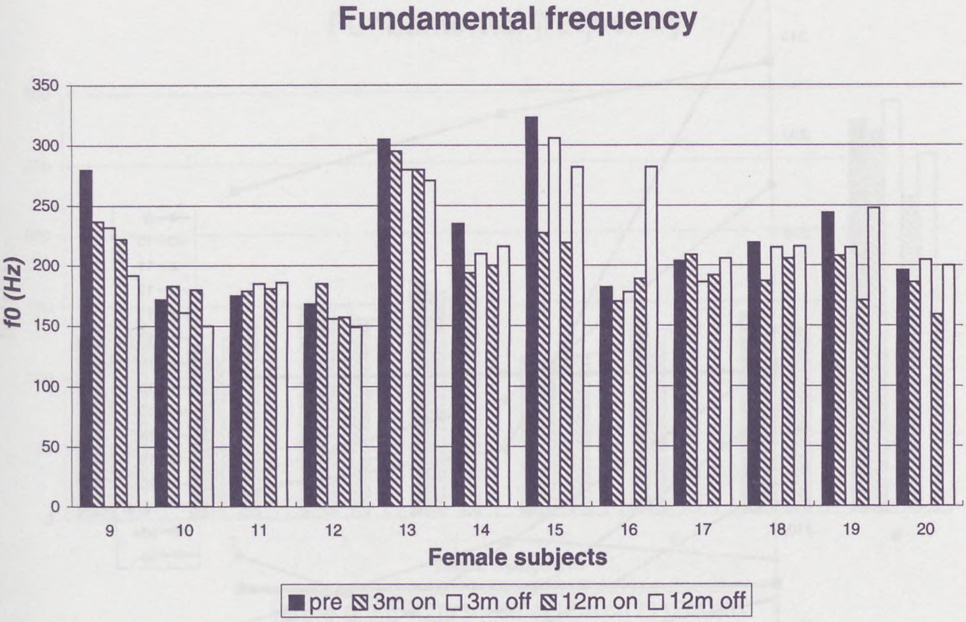

Fig. 1. Individual mean fundamental frequency in Hz for twelve female subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on and off.

Fig. 2 shows that the largest changes after implantation primarily occur for the female subjects with these high f_0 values. Further, we notice a non-significant decrease in the differences between the female subjects after implantation. The group mean for the female subjects was 225 Hz pre-implantation. This value decreased to 205 Hz and 196 Hz for the three and twelve months post-implantation conditions, respectively. These values are closer to the normal group mean of 199 Hz. No significant difference was found between switching on and off the implant at three and twelve months post-implantation. Nevertheless, a considerable increase in f_0 after switching the implant off was noted in the female subjects 15, 16, 19, 20, in particular at twelve months post-implantation (Fig. 1). For subjects 15, 16 and 19 switching off the implant resulted in f_0 values above the normal range at twelve months post-implantation.

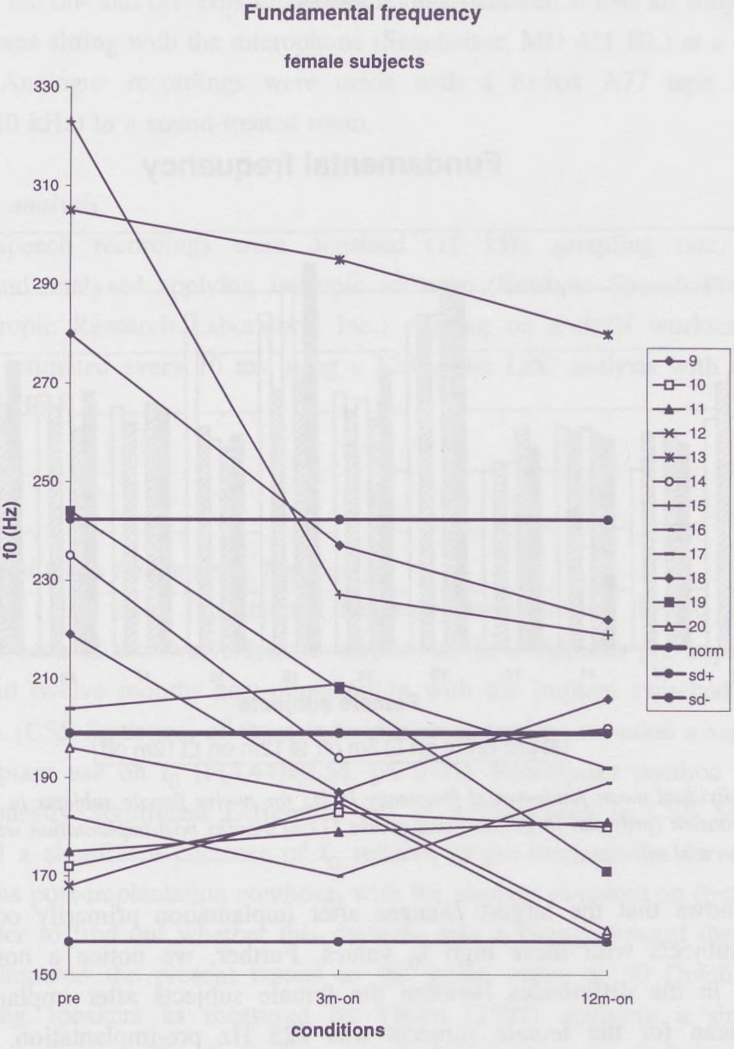

Fig. 2. Individual mean fundamental frequency in Hz for twelve female subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on, together with the normal group mean and the group mean plus and minus one standard deviation (sd) for normal-hearing female speakers.

Fig. 3 shows the individual mean fundamental frequency values for the eight male subjects in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. There was no significant condition effect.

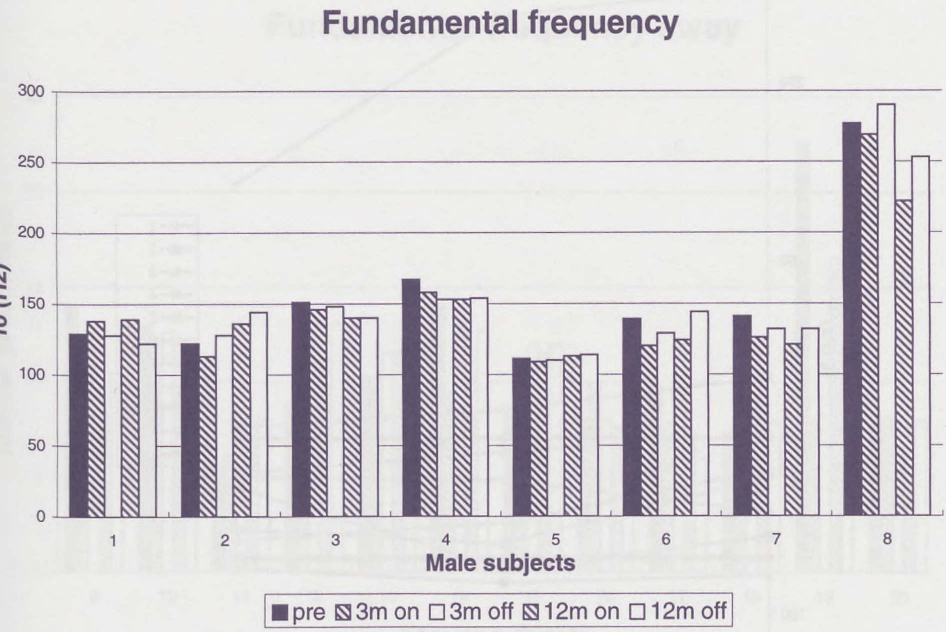

Fig. 3. Individual mean fundamental frequency in Hz for eight male subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on and off.

Fig. 4 presents these f_0 values of all male subjects in the condition pre-implantation and the two post-implantation conditions with the implant switched on, together with the normal group mean f_0 for male speakers and this group mean plus and minus one standard deviation derived from Tielen (1992). This figure shows that most male subjects had f_0 values within the normal range both pre-implantation and post-implantation. Pre-implantation only one subject (8) had a f_0 value which fell markedly outside the normal range for male speakers. At twelve months post-implantation with the implant switched on this subject showed a considerable decrease in the high value of f_0. Interestingly, switching off the implant for this subject at twelve months post-implantation resulted in an increase of f_0, as shown in Fig. 3.

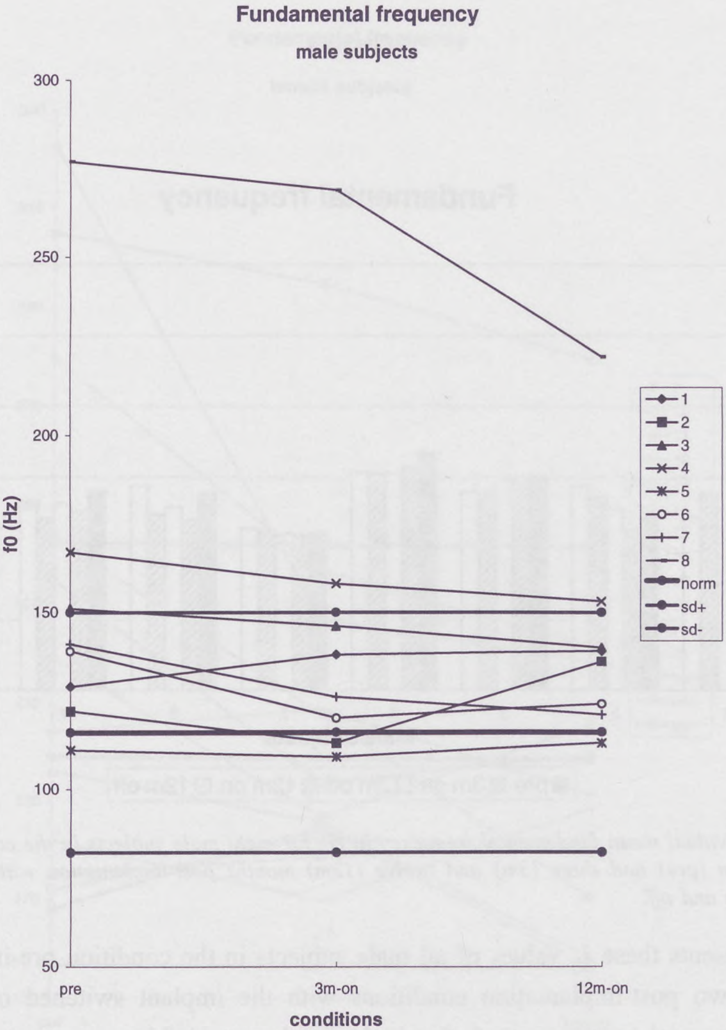

Fig. 4. Individual mean fundamental frequency in Hz for eight male subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on, together with the normal group mean and the group mean plus and minus one standard deviation (sd) for normal-hearing male speakers.

4.3.2 Individual sway in fundamental frequency

Restoring auditory feedback may also have an effect on the variation in f_0 while reading the text. Therefore, we determined the 90% range of fundamental frequency deflections, the f_0 sway, per subject in the conditions pre-implantation and post-implantation again at three and twelve months with the implant switched on and off. In Fig. 5 the f_0 sway is presented for the twelve female subjects.

ANOVA of these data revealed no significant condition effect (p=0.2).

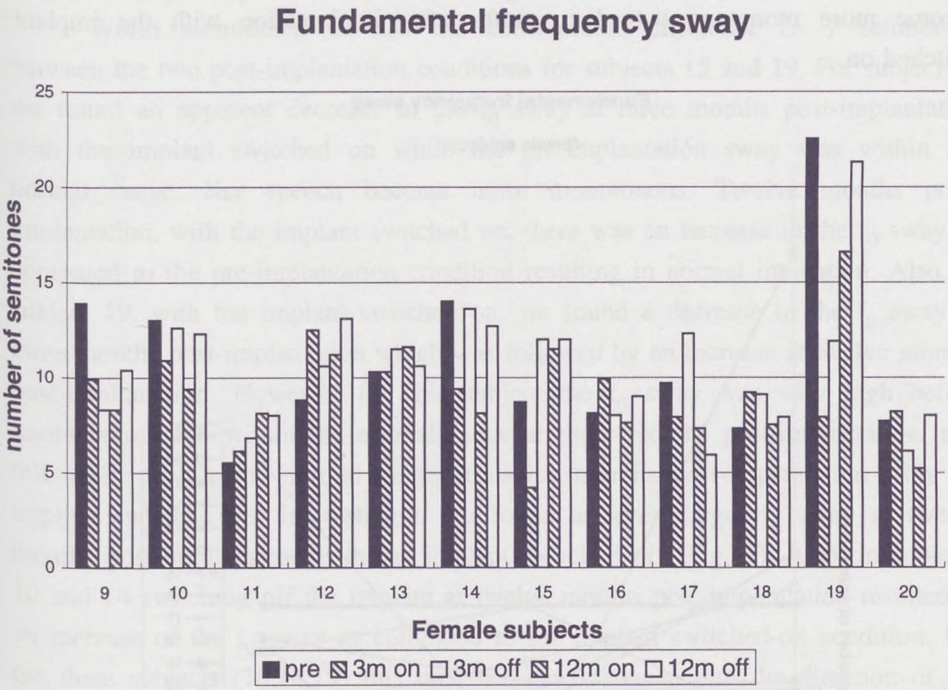

Fig. 5. The fundamental frequency sway, the 90% range of fundamental frequencies, in semitones for twelve female subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on and off.

In Fig. 6 the individual sway in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on is presented together with the group mean sway and this group mean plus and minus one standard deviation for normal-hearing female speakers (Tielen, 1992). Three months post-implantation we found a significant decrease ($p<0.05$) in the between-subjects differences in sway (F-test, df1=df2=11). Twelve months post-implantation the decrease in between-subject differences failed to reach the 5% significance level (p=0.09). Pre-implantation, 58% of the subjects fell within the normal range, while this number increased to 83% at both three and twelve months post-implantation.

Further, Fig. 6 shows great variability in the effect of cochlear implantation on the f_0 sway depending on the pre-implantation values. In six subjects the f_0 sway decreased twelve months after implantation with the implant switched on. In three of these six subjects (9,14,19) this meant an improvement in intonation, considering the normal sway in fundamental frequency for normal-hearing Dutch female speakers of about 10 semitones (Tielen, 1992). However, in subject 20 speech has become more monotonous twelve months after implantation with the implant switched on.

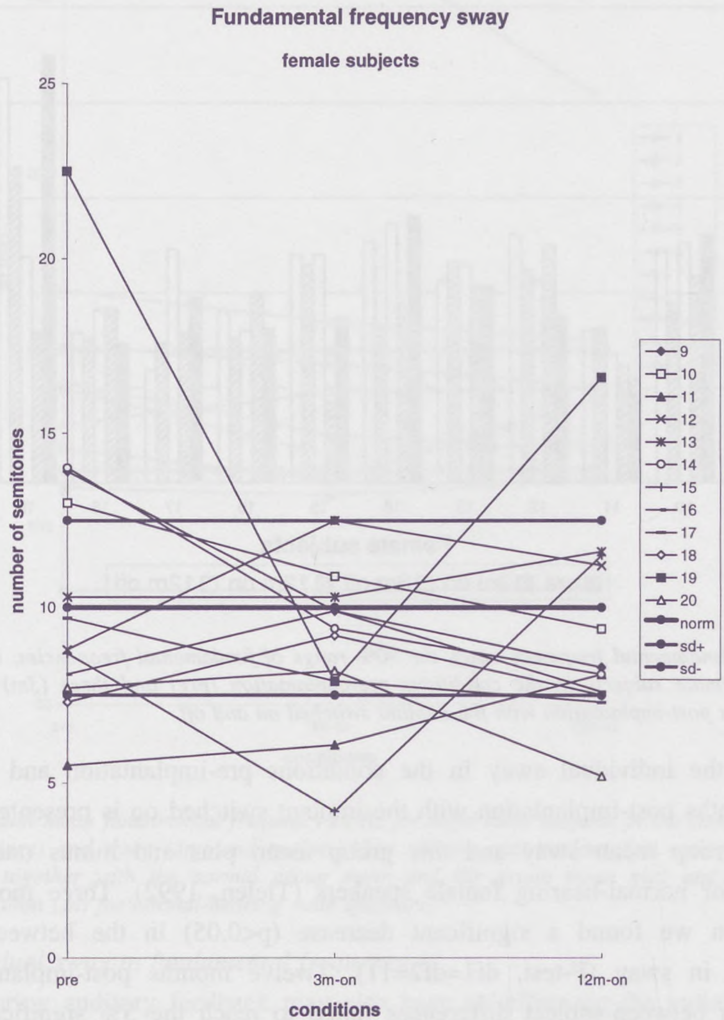

Fig. 6. The fundamental frequency sway, the 90% range of fundamental frequencies, in semitones for twelve female subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on, together with the normal group mean and the group mean plus and minus one standard deviation (sd) for normal-hearing female speakers.

In subject 11 we note an increase in the f_0 sway twelve months after implantation versus pre-implantation, which meant an obvious improvement in this subject who, pre-implantation, was speaking too monotonously.

Worth mentioning is also the considerable difference (> 7 semitones) between the two post-implantation conditions for subjects 15 and 19. For subject 15 we found an apparent decrease in the f_0 sway at three months post-implantation with the implant switched on while the pre-implantation sway was within the normal range. Her speech became more monotonous. Twelve months post-implantation, with the implant switched on, there was an increase in the f_0 sway as compared to the pre-implantation condition resulting in normal intonation. Also, in subject 19, with the implant switched on, we found a decrease in the f_0 sway at three months post-implantation which was followed by an increase at twelve months post-implantation. However, for this subject the f_0 sway was very high before implantation, fell within the normal range at three months post-implantation, and fell again outside the normal range at twelve months post-implantation with the implant switched on. Interestingly, we found an even larger f_0 sway at twelve months post-implantation with the implant switched off (Fig. 5). Also, in subjects 10 and 14 switching off the implant at twelve months post-implantation resulted in an increase of the f_0 sway as compared to the implant switched-on condition. For the three subjects (10,14,19) this increase was a change into the direction of the pre-implantation values of these subjects.

The fundamental frequency sway for the male subjects in the five conditions is presented in Fig. 7. As for the female subjects no significant condition effect was found. In Fig. 8 the f_0 sway in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on is presented together with the group mean and the group mean plus and minus one standard deviation for normal-hearing male speakers (Tielen, 1992). We found no significant change in mean f_0 sway toward the norm value for male speakers. Nonetheless, for subjects 2 and 8 with f_0 sways above normal we found a substantial decrease in the f_0 sway twelve months after implantation, which corresponded to subjectively improved intonation. In subject 4 we found at first a decrease in the f_0 sway at three months post-implantation versus pre-implantation resulting in monotonous speech. At twelve months post-implantation his intonation covered a wider range. The speech of subject 7, which was monotonous pre-implantation showed no improvement post-implantation.

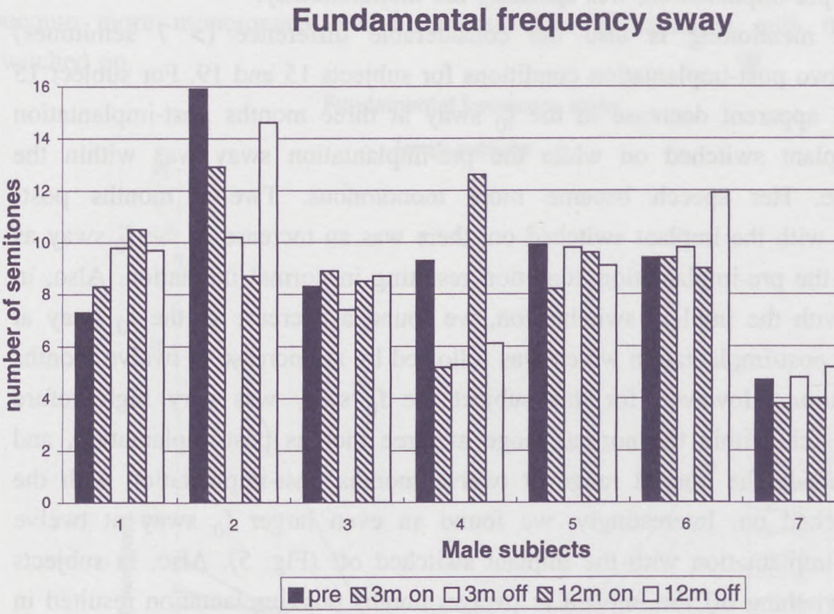

Fig. 7. The fundamental frequency sway, the 90% range of fundamental frequencies, in semitones for eight male subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on and off.

In summary, the f_0 sway averaged over the groups of twelve females and eight males in the conditions pre-implantation and twelve months post-implantation with the implant switched on are presented in Table 2. Twelve months post-implantation we note a decrease in f_0 sway as compared to pre-implantation for both the female and the male subjects.

Table 2. The sway, 90% range of fundamental frequency, expressed in Hz and in semitones averaged over 12 females and 8 males during text reading in the conditions pre-implantation and twelve months post-implantation with the implant switched on.

sway in	pre-implantation Hz	semitones	12m post-implantation Hz	semitones
females	14	143 - 315	12	136 - 278
males	19	94 - 275	15	97 - 230

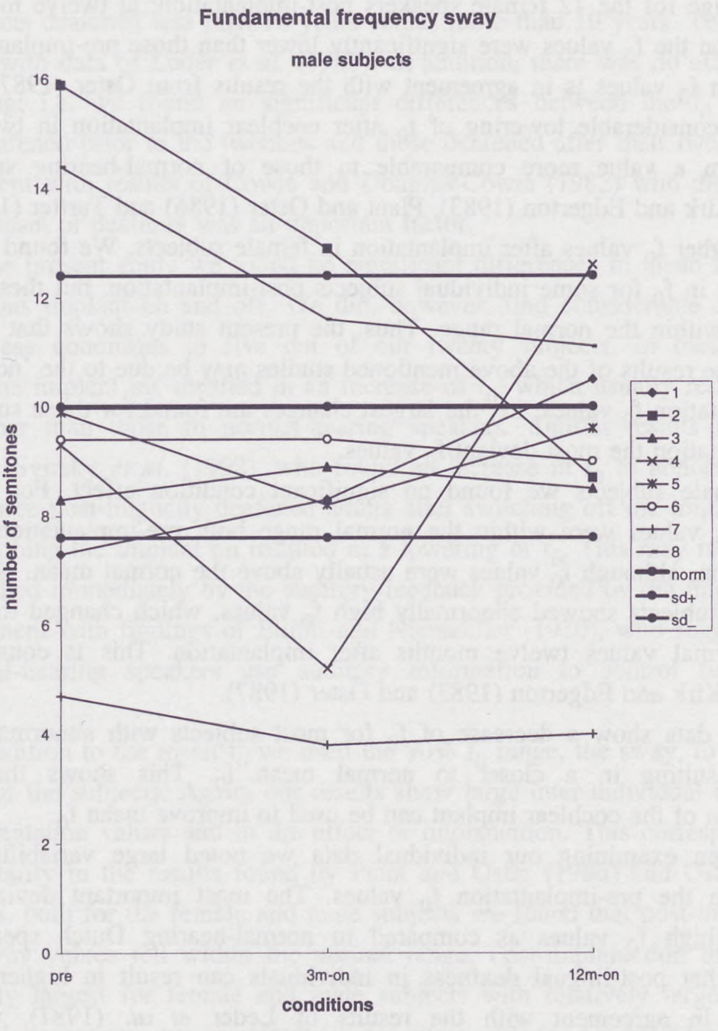

Fig. 8. The fundamental frequency sway, the 90% range of fundamental frequencies, in semitones for eight male subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on, together with the normal group mean and the group mean plus and minus one standard deviation (sd) for normal-hearing male speakers.

4.4 Discussion

In our group of 20 subjects we found a change of f_0 into the direction of the normal range for the 12 female speakers post-implantation; at twelve months post-implantation the f_0 values were significantly lower than those pre-implantation. The decrease in f_0 values is in agreement with the results from Oster (1987) who also noticed a considerable lowering of f_0 after cochlear implantation in two subjects, resulting in a value more comparable to those of normal-hearing speakers. In contrast, Kirk and Edgerton (1983), Plant and Oster (1986) and Tartter (1989) found slightly higher f_0 values after implantation in female subjects. We found only slight increments in f_0 for some individual subjects post-implantation, but these f_0 values remained within the normal range. Thus, the present study shows that differences between the results of the above mentioned studies may be due to the 'normality' of pre-implantation f_0 values; i.e. the largest changes are found for those subjects with pre-implantation the most deviant f_0 values.

For the male subjects we found no significant condition effect. For most male subjects f_0 values were within the normal range both pre-implantation and post-implantation, although f_0 values were usually above the normal mean. Nonetheless, two male subjects showed abnormally high f_0 values, which changed toward more nearly normal values twelve months after implantation. This is consistent with results of Kirk and Edgerton (1983) and Oster (1987).

Thus, our data show a decrease of f_0 for most subjects with abnormally high f_0 values, resulting in a closer to normal mean f_0. This shows that auditory information of the cochlear implant can be used to improve mean f_0.

When examining our individual data we noted large variability between subjects in the pre-implantation f_0 values. The most important deviations were relatively high f_0 values as compared to normal-hearing Dutch speakers. This indicates that post-lingual deafness in individuals can result in higher f_0 values, which is in agreement with the results of Leder *et al.* (1987), who found significantly higher f_0 values in 21 profoundly deaf men. They suggested that even when normal voice quality had been obtained before deafness, a profound deafness can cause f_0 to change into a direction similar to f_0 values found in the pre-lingual deaf. However, Waldstein (1990) found f_0 of post-lingually deafened subjects to agree largely with values obtained in normal-hearing speakers. This discrepancy between different studies might again be explained by the large inter-individual differences in f_0 values among post-lingually deafened subjects as seen in this study pre-implantation. A possible explanation for these interindividual differences might be the duration of deafness. However, we found no significant differences in mean f_0 for subjects deafened less than 10 years versus more than 10 years. These results are in line with data of Leder *et al.* (1987). In addition, there was no effect of age of deafening; i.e. we found no significant differences between the f_0 values of subjects deafened prior to the twenties and those deafened after their twenties. This is inconsistent with results of Cowie and Douglas-Cowie (1982) who did find that the age at onset of deafness was an important factor.

In the present study we found no significant differences in mean f_0 between the conditions implant on and off. We did, however, find considerable differences between these conditions in five out of our twenty subjects. In these subjects switching the implant off resulted in an increase of f_0, which usually resulted in f_0 values higher than those in normal-hearing speakers. Similar results have been reported by Svirsky *et al.* (1992), who found an increase in f_0 to abnormally high values in three post-lingually deafened adults after switching off the implant for 24 hours. Switching the implant on resulted in a lowering of f_0. This may indicate that f_0 is controlled immediately by the auditory feedback provided by the implant. This is in agreement with findings of Elliott and Niemoeller (1970), who suggested that also normal-hearing speakers use auditory information to control fundamental frequency.

In addition to the mean f_0 we used the 90% f_0 range, the sway, to depict the intonation of the subjects. Again, our results show large inter-individual differences in pre-implantation values and in the effect of implantation. This corresponds with the dissimilarity in the results found by Plant and Oster (1986) and Oster (1987). Nonetheless, both for the female and male subjects we found that post-implantation more f_0 sway values fell within the normal range. Post-implantation the changes were usually largest for female and male subjects with relatively large sways of fundamental frequency pre-implantation as compared to normal-hearing Dutch speakers. Apparently, these implant users could employ auditory information of the implant to better control their intonation pattern. This is also true for three out of four subjects in which intonation was too monotonous pre-implantation.

In comparing three and twelve months data obtained with the implant switched on we found no statistically significant group differences. However, in three subjects (4, 15, 19) considerable differences were found. We noted a large decrease in f_0 sway at three months post-implantation followed by an increase at twelve months post-implantation. In subject 19, who demonstrated an extremely large f_0 sway pre-implantation overcompensation might have played a role at three months post-implantation. In the other subjects auditory input may have been disruptive at first resulting in too monotonous intonation.

No significant differences in f_0 sway between the conditions implant on and off were found. However, in subjects with large f_0 sways pre-implantation we often noted a considerable increase in f_0 sway into the direction of the pre-implantation values after switching off the implant, even though the implant was switched off for only half an hour. Presumably, twelve months after implantation these subjects still depend on the auditory feedback of the implant to control their intonation. Again, this is in agreement with the results of Elliot and Niemoeller (1970), who suggested that normal-hearing speakers depend on auditory information to control their voice fundamental frequency.

4.5 Conclusions

In summary, our study shows that in those subjects where f_0 was found outside the normal range it was always too high. Post-implantation, with the implant switched on, we found that abnormally high f_0 values pre-implantation (for females higher than about 245 Hz; for males higher than about 150 Hz) changed toward the norm values.

Post-implantation the sway in f_0 generally improved for subjects with abnormal f_0 sways, reflecting better intonation. Primarily, this improvement was associated with a decrease in sway.

For all subjects together no significant short-term effects of switching the implant on and off were found. Nonetheless, in some individual subjects considerable differences between these conditions were seen, demonstrating values closer to normal when the implant was switched on.

Finally, we noted large interindividual variability in the pre-implantation f_0 values, as well as in the effect of cochlear implantation on f_0.

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CHAPTER 5

EFFECT OF COCHLEAR IMPLANTATION ON *NASALITY IN POST-LINGUALLY* DEAFENED ADULTS

Effect of cochlear implantation on nasality in post-lingually deafened adults.

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Abstract

The present study addresses the effect of cochlear implantation on nasality in twenty-one post-lingually deafened Dutch subjects. All subjects received the Nucleus 22 implant (MSP-version). Speech recordings were made pre-implantation and three and twelve months post-implantation with the implant switched on and off. Nasality measurements were performed on a standard text and on two sentences without nasal phonemes.

The results show that post-lingual deafness in individuals can result in a deviant degree of nasality in speech production. However, the nasalance value of 86% of the subjects of our study fell within the normal range defined as the mean plus or minus two standard deviations of the normal population. After implantation we found no statistically significant effect of implant use. However, individual nasality values outside the normal range may improve. Furthermore, twelve months post-implantation we found a significant decrease in the variability of the nasalance values obtained for two sentences without nasal phonemes.

5.1 Introduction

Several studies on speech production in post-lingually deafened adults have shown disruptive effects on speech production caused by the loss of auditory feedback. In this study we restrict ourselves to one aspect of speech production: the degree of nasality. Speech of the pre-lingually deaf often deviates in this aspect (Nickerson, 1975; Kirk and Edgerton, 1983). Restoration of some auditory feedback by cochlear implantation may improve nasalization.

Leder and Spitzer (1990) evaluated speech production of 25 post-lingually deafened adult males and 10 male controls using 15 listeners who received training in speech-language pathology. They found that speech- and language pathologists rated the post-lingually deafened as significantly deviant from the control subjects on the nasality variable. No information, however, was given on the hypo/hyper nasality distinction.

Also, Plant and Hammarberg (1983) used perceptual analysis to judge speech production. When reading a short story they found in one of the three post-lingually deafened subjects that voice quality was characterized as nasalized. Plant (1993) noted that two out of ten subjects were judged to be hypernasal. In the other eight subjects no deviations with respect to nasality were found. Binnie *et al.* (1982) found an increase in nasalization in a five-year-old boy following a sudden deafness. Spectrographic records showed increased nasal co-articulation, resulting in words containing nasal consonants sounding hypernasal. They did not find nasalization in non-nasal contexts. Cowie and Douglas-Cowie (1983) also reported nasality problems in post-lingually deafened subjects resulting primarily in hypernasal speech.
Thus, on the basis of the literature reporting mostly perceptual judgments we conclude that post-lingual deafness can variably cause deviations in nasality.

So far, little research has been directed towards the effects of cochlear implantation on nasality. Plant and Oster (1986) reported a decrease of nasalization in a post-lingually deafened subject two years after implantation with a single-channel cochlear implant. In our study we will therefore address the following questions:

1. What is the effect of post-lingual deafness on nasality in a group of twenty-one subjects?
2. What is the effect of cochlear implantation with a multi-channel implant on nasality of these subjects?

Most research on nasality is based on subjective judgements. In order to answer the above questions we will use objective measurements, because subjective scaling of the degree of nasality has been found to be a very difficult task. Also, it requires a large group of listeners to achieve reliable results (Counihan and Cullinan, 1972).

5.2 Methods

5.2.1 Subjects

Recordings were made for twenty-one post-lingually deafened Dutch speakers (six males and fifteen females). Their age varied from 27 to 73 years with a mean age of 48 years. All subjects received the Nucleus 22 cochlear implant

Table 1. Subject and implant characteristics ordered according to gender and duration of deafness

	gender	age	etiology	duration of deafness in years	number of active electrodes 3m	12m	mean dynamic range (dB) 3m	12m	stimulus strategy 3m	12m	CVC phoneme score (%) 3m	12m
2	m	64	progressive	1	19	18	7.0	10.2	mpeak	mpeak	55.9	40.7
21	m	29	cogan syndrom	2	22	22	3.6	3.4	mpeak	mpeak	38.7	24.8
22	m	73	otosclerosis	7	20	20	3.7	5.0	mpeak	mpeak	26.7	33.0
4	m	28	meningitis	9	20	20	3.3	4.7	mpeak	mpeak	19.0	28.5
23	m	27	meningitis	22	22	22	1.3	2.1	mpeak	mpeak	9.4	6.4
8	m	51	meningitis	40	22	22	4.9	5.6	mpeak	mpeak	0.0	21.5
24	f	46	genetically	1.5	22	22	2.6	2.6	mpeak	mpeak	19.4	26.6
25	f	43	unkown	2	18	18	3.4	5.6	mpeak	speak	4.2	7.6
26	f	43	meningitis	2	5	5	5.4	5.4	$f_0/F_1/F_2$	$f_0/F_1/F_2$	9.7	19.4
9	f	65	otosclerosis	2	16	16	4.9	4.3	mpeak	mpeak	13.0	23.8
10	f	52	meningitis	3	20	15	7.6	7.4	mpeak	mpeak	28.5	28.8
11	f	40	otitis	4	21	16	4.4	1.2	mpeak	mpeak	13.2	27.1
12	f	37	progressive	5	18	18	2.8	2.1	mpeak	mpeak	32.5	35.9
13	f	33	unknown	5	18	14	5.3	3.5	mpeak	$f_0/F_1/F_2$	2.7	3.5
14	f	49	otosclerosis	6	20	20	3.5	3.5	mpeak	mpeak	35.1	30.0
15	f	54	unknown	7	22	22	4.3	4.3	mpeak	mpeak	45.8	43.1
16	f	68	unknown	8	22	20	4.5	2.8	mpeak	$f_0/F_1/F_2$	22.6	22.3
17	f	40	progressive	11	20	20	3.9	3.0	mpeak	mpeak	36.0	41.5
27	f	55	progressive	24	22	22	7.9	7.9	mpeak	mpeak	32.5	32.5
19	f	56	unknown	41	16	12	1.6	2.8	mpeak	mpeak	9.4	13.0
20	f	57	meningitis	47	20	20	2.3	3.2	mpeak	mpeak	2.7	11.8

(MSP-version). After implantation they received only auditory training. No explicit speech therapy was given. Additional information about the subjects is given in Table 1.

5.2.2 Instrumentation

Measurements were performed using the model 6200 Nasometer manufactured by Kay Electronics. The Nasometer is an instrument designed to measure the degree of nasality in speech. Recently, this instrument has received increasing acceptance (Nellis *et al.*, 1992; Dalston *et al.*, 1991, 1993; Haapanen, 1991, 1994, 1996). The principle of the nasometer is based on comparison of the nasal and oral components of a subjects' speech. The two components are separated by a flat plate between the air streams from nose and mouth. The intensities of the nasal and oral components are measured and used to calculate the ratio: nasal/(nasal + oral). This ratio is expressed in the Nasalance[1] Percentage.

5.2.3 Materials

The speech material consisted of a standard text, containing both oral and nasal phonemes. The normative data from this text were derived from Weyer and Slis (1991). They found a normal mean nasalance percentage of 32.0 with a standard deviation of 5.2. Additionally, the subjects had to read two sentences without nasal phonemes because the literature indicates that the nasometer gives valid correlates of perceptual judgements for these non-nasal sentences (Dalston *et al.*, 1991; Haapanen, 1994; Fletcher, 1976). As a reference for these sentences we used the normal mean value of 11.8% for the non-nasal text from Weyer and Slis (1991).

5.2.4 Procedure

Measurements were made pre-implantation and three and twelve months post-implantation with the implant switched on and off. The measurements with the implant switched off were performed immediately after switching off the implant. The order of on- and off- conditions was counterbalanced across all subjects.

[1] the term 'nasalance' is introduced by Kay Electronics

5.2.5 Data analysis

The mean nasalance score was computed for each subject reading the standard text and the two non-nasal sentences. The effect of the five different conditions (pre-implantation and three and twelve months post-implantation with the implant switched on and off) on the mean nasalance scores was tested applying analysis of variance (CSS Statistica). Whenever a significant effect was found post-hoc analysis (Tukey's Honestly Significant Difference test, HSD) was performed. Additionally, the nasalance scores measured for the standard text were compared with normative data derived from Weyer and Slis (1991).

Table 2. Mean nasalance scores in % when reading a standard text for twenty-one subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on and off.

subject	pre	3m on	3m off	12m on	12m off
2	32	37	41	34	41
21	33	33	30	33	33
22	24	22	22	18	19
4	29	42	40	27	39
23	45	42	39	33	39
8	25	25	25	28	29
24	26	27	26	28	25
25	32	38	36	40	39
26	36	38	39	35	38
9	35	38	40	36	33
10	25	26	28	28	29
11	50	42	37	46	37
12	34	32	32	26	29
13	31	32	31	27	31
14	30	29	33	30	30
15	31	28	32	30	29
16	33	33	34	32	35
17	26	29	27	30	29
27	30	42	45	35	44
19	41	43	37	40	36
20	18	23	25	21	20
Mean	32	33	33	32	33

5.3 Results

5.3.1 Nasalance scores reading a standard text

The mean nasalance scores of the twenty-one subjects reading the standard text in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off are presented in Table 2. ANOVA (CSS Statistica) for all five speech conditions revealed no significant effect.

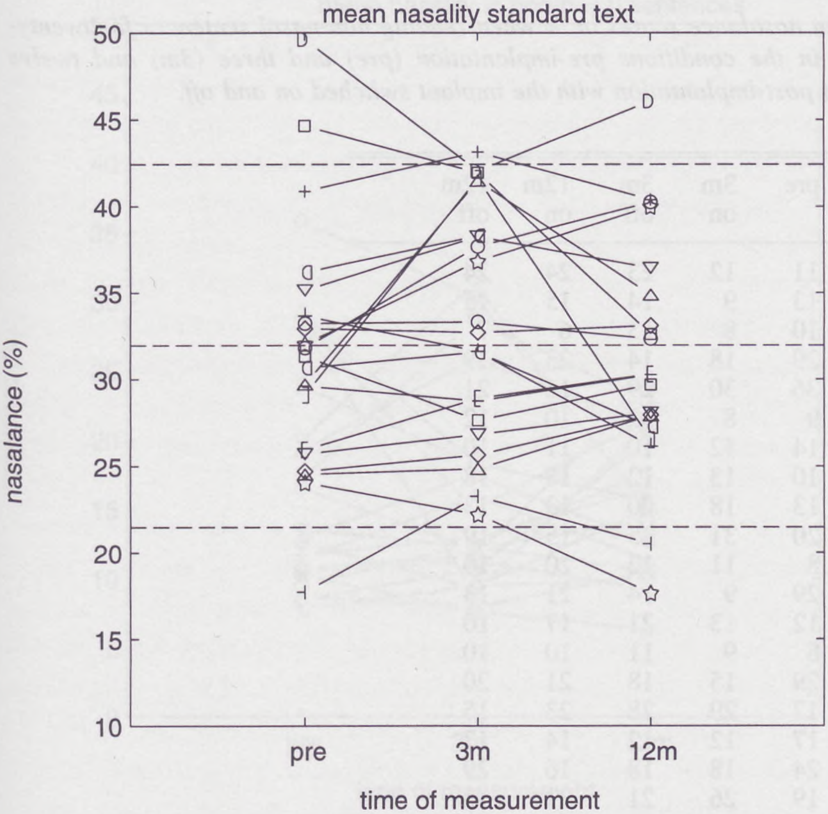

Fig. 1: Mean nasalance scores in % of twenty-one subjects when reading a standard text in the conditions pre-implantation (pre) and three (3m) and twelve months (12m) post-implantation with the implant switched on, together with the normal mean and range.

Fig. 1 shows the mean nasalance scores of all subjects when reading the standard text in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on. Additionally, the dotted lines in Fig. 1 show the normal mean and twice the standard deviation of forty Dutch subjects derived from Weyer and Slis (1991). Pre-implantation three subjects (11,20,23) fell outside the normal range. Three months post-implantation these three subjects and all other subjects fell within the normal range. However, twelve months post-implantation we found a small relapse for two of these three subjects. Additionally, at twelve months post-implantation one subject (22) showed a decrease in the nasalance value resulting in hyponasal speech.

Table 3. Mean nasalance scores in % when reading non-nasal sentences for twenty-one subjects in the conditions pre-implantation (pre) and three (3m) and twelve (12m) months post-implantation with the implant switched on and off.

subject	pre	3m on	3m off	12m on	12m off
2	11	12	23	24	24
21	13	9	14	15	15
22	10	8	13	6	7
4	29	18	14	23	19
23	36	30	29	16	21
8	9	8	12	10	12
24	14	12	10	11	10
25	10	13	12	18	18
26	13	18	20	13	13
9	20	31	25	15	19
10	8	11	12	20	10
11	29	9	14	21	13
12	12	13	21	17	10
13	8	9	11	10	10
14	29	15	18	21	20
15	17	29	28	23	15
16	17	12	12	14	17
17	24	18	18	16	29
27	19	26	21	21	16
19	10	11	12	9	33
20	11	16	22	11	14
Mean	17	16	17	16	16

5.3.2 Nasalance scores reading non-nasal sentences

The mean nasalance scores of all subjects reading non-nasal sentences pre-implantation and three and twelve months post-implantation with the implant switched on and off are presented in Table 3. We found no significant condition effect. However, Fig. 2 shows that twelve months post-implantation with the implant switched on the subjects were significantly less variable ($p<0.05$; F-test, df1=df2=20) in their performance as compared to the pre-implantation condition. Additionally, we found that pre-implantation most nasalance values were higher than the mean value of about 12% for normal-hearing subjects.

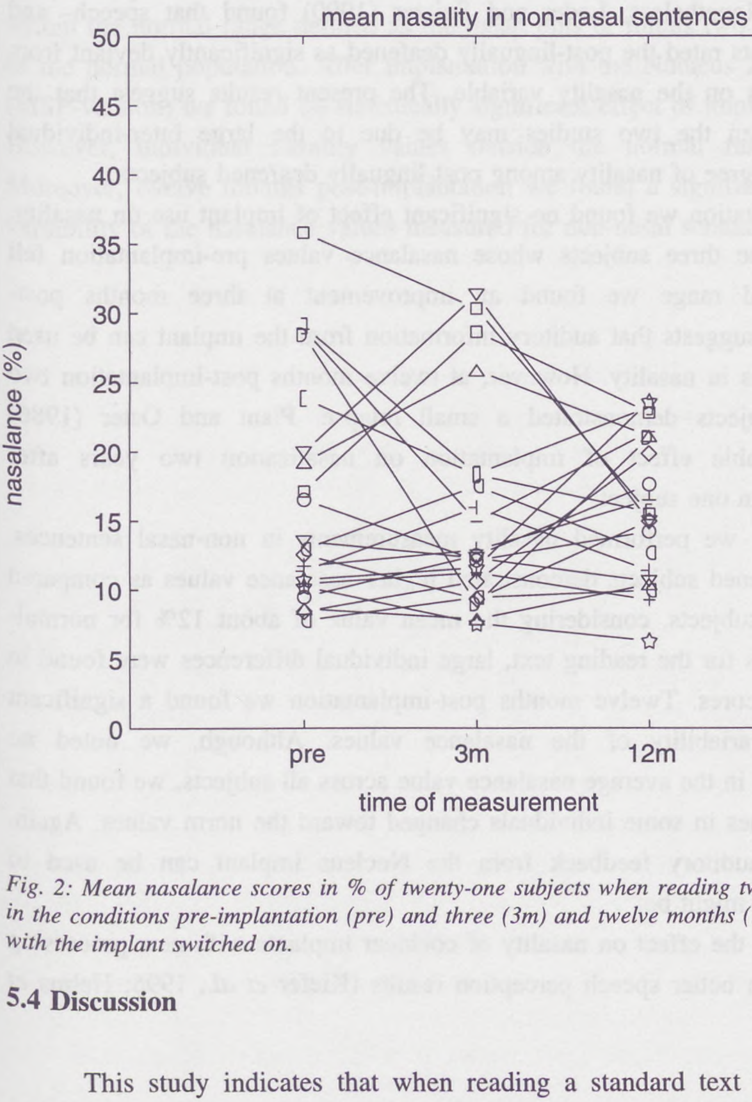

Fig. 2: Mean nasalance scores in % of twenty-one subjects when reading two non-nasal sentences in the conditions pre-implantation (pre) and three (3m) and twelve months (12m) post-implantation with the implant switched on.

5.4 Discussion

This study indicates that when reading a standard text three subjects in a group of twenty-one post-lingually deafened subjects showed deviations in the nasality measurements larger than the normal range of two standard deviations. Two subjects were found to be hypernasal and one to be hyponasal. Most of our subjects showed no effect of post-lingual deafness on the degree of nasality in speech. These results are similar to those of Plant (1993) who noted two out of ten subjects to be hypernasal. However, where Plant used subjective judgements we used objective measurements. In examining the pre-operative data we found large individual differences, but most data did not exceed the range of values found in normal-hearing subjects. Nonetheless, Leder and Spitzer (1990) found that speech- and language pathologists rated the post-lingually deafened as significantly deviant from the control subjects on the nasality variable. The present results suggest that the dissimilarity between the two studies may be due to the large inter-individual variability in the degree of nasality among post-lingually deafened subjects.

After implantation we found no significant effect of implant use on nasality. Nonetheless, for the three subjects whose nasalance values pre-implantation fell outside the normal range we found an improvement at three months post-implantation. This suggests that auditory information from the implant can be used to correct deviations in nasality. However, at twelve months post-implantation two of these three subjects demonstrated a small relapse. Plant and Oster (1986) reported a favourable effect of implantation on nasalization two years after implantation, be it in one subject.

Additionally, we performed nasality measurements in non-nasal sentences. Post-lingually deafened subjects demonstrated higher nasalance values as compared to normal-hearing subjects, considering the mean value of about 12% for normal-hearing subjects. As for the reading text, large individual differences were found in the pre-operative scores. Twelve months post-implantation we found a significant decrease in the variability of the nasalance values. Although, we noted no significant decrease in the average nasalance value across all subjects, we found that high nasalance values in some individuals changed toward the norm values. Again, this implies that auditory feedback from the Nucleus implant can be used to improve nasality. It might be interesting to study the effect on nasality of cochlear implants with new processing strategies with even better speech perception results (Kiefer *et al.*, 1996; Helms *et al.*, 1997).

5.5 Conclusions

Post-lingual deafness in individuals can result in a deviant degree of nasality in speech production. However, the nasalance values of 86% of our subjects fell within the normal range defined as the mean plus or minus two standard deviations of the normal population. After implantation with the Nucleus 22 cochlear implant (MSP-version) we found no statistically significant effect of implant use on nasality. However, individual nasality values outside the normal range may improve. Moreover, twelve months post-implantation we found a significant decrease in the variability of the nasalance values measured for non-nasal sentences.

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CHAPTER 6

PERCEPTUAL EVALUATION OF SPEECH PRODUCTION OF *POST-LINGUALLY DEAFENED ADULTS* USING A COCHLEAR IMPLANT

Perceptual evaluation of speech production of post-lingually deafened adults using a cochlear implant

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Abstract

The effect of cochlear implantation on the speech quality of twenty post-lingually deafened Dutch subjects was studied, using perceptual judgements of a large panel of students of speech and language pathology. All subjects received the Nucleus 22 cochlear implant (3 WSP and 17 MSP processors). Speech recordings were made pre-implantation and three and twelve months post-implantation with the implant switched on and off. The speech material consisted of a sample of conversational speech. Speech production was judged on the basis of 21 questions, involving both segmental and suprasegmental aspects of speech.

The results show that cochlear implantation with a Nucleus 22 implant indeed improves speech quality of post-lingually deafened subjects. The largest improvements were seen in the suprasegmental aspects, but also vowel production improved. Post-implantation we found significant lower ratings with the implant switched off versus switched on, implying that twelve months after implantation auditory information from the implant is still used to control speech production. Also, this study showed that pre-implantation subjects with a duration of profound hearing loss of less than 10 years had better speech quality than those with a profound hearing loss of more than 10 years. Finally, this study showed large interindividual differences between the subjects and in the effect of cochlear implantation on speech quality.

6.1 Introduction

Post-lingually acquired deafness often results in a reduction in the quality of speech production (Cowie *et al.* 1982, 1983; Waldstein, 1990; Plant, 1983,1993; Leder and Spitzer, 1990; Read, 1989; Lane and Webster, 1991; Langereis *et al.*, 1997a,b,c). The degree to which the quality of speech is affected, however, varies considerably among individuals (Read, 1989; Cowie *et al.* 1982). Adverse effects of post-lingually acquired deafness have been found with respect to both suprasegmental (Leder *et al.*, 1986, 1987a,b; Ball *et al.*, 1990) and segmental

(Monsen, 1976; Waldstein, 1990; Plant, 1993; Lane and Webster, 1991; Zimmermann and Rettaliata, 1981) aspects of speech production.

Several researchers (Binnie *et al.*, 1982; Plant and Hammarberg, 1983; Plant, 1984; Leder and Spitzer, 1990, Plant, 1993) reported about the effect of post-lingual deafness on speech production using perceptual judgements of segmental and suprasegmental aspects. Binnie *et al.* (1982) studied the speech of a five-year-old child nine months after a sudden deafness. They found that the child spoke with a slow, monotonous high pitched voice. In addition, they found the following changes at the segmental level: syllabification of consonants, diphthongization, heavy aspiration during consonant release, cluster reduction and glottal stopping.

Plant and Hammarberg (1983) used perceptual judgements of four speech therapists in the evaluation of speech produced by three post-lingually deafened subjects. The therapists judged the following factors: overall pitch, pitch contour and stress pattern, voice quality, articulation and tempo. Speech of the two subjects deafened before puberty seemed more adversely influenced than speech of one subject deafened during middle-age. In the latter subject deteriorations appeared mainly in the use of intonational contrasts, with articulation considered to be normal. Plant (1984) compared speech fragments of a 14-year-old male subject deafened at the age of 11 recorded at two and 30 months after the onset of deafness with an adolescent male control subject deafened at the age of five. Twelve listeners rated the fragments on a seven-point scale, examining: pitch, voice quality, intonation and speech rate. The recording two months after the onset of deafness was rated as almost normal, whereas 30 months after onset speech was rated as deviant with pitch and intonation mostly affected. Interestingly, the deviations were in the direction of the ratings for the deaf control subject. In a study by Plant (1993) listeners judged the utterances of ten post-lingually deafened and ten normal hearing subjects as belonging to either category. In addition, they were asked to give those aspects of an individual's speech which indicated that a speaker was deafened. About 20% of the judgements were based on ratings of changes in voice quality, 35% on suprasegmental deviations and 45% on segmental errors. These results are in accordance with results of Leder and Spitzer (1990). They investigated the effect of post-lingual deafness on speech production of 25 male subjects. Ten normal-hearing male subjects served as controls. All subjects were judged by 15 listeners on seven variables. Leder and Spitzer (1990) found that the post-lingually deafened were judged significantly different from the normal-hearing subjects, showing deteriorations in both suprasegmental and segmental aspects of speech production. In decreasing order of importance the deteriorations concerned: intonation, pitch, speech rate, nasality, vowel duration, articulation and intensity. However, their results did not demonstrate extensive articulation errors. In summary, the literature on perceptual evaluations indicates that post-lingually deafened subjects may show a variety of deteriorations in speech production resulting from the loss of auditory feedback.

Cochlear implants partially restore the auditory feedback and they can have a positive effect on speech production of the post-lingual deaf. Subjective evaluation by a speech therapist of speech produced by 30 post-lingually deafened adults before and after implantation with the UCH/RNID single channel implant was studied by Read (1989). Pre-implantation the suprasegmental aspects of speech production were most affected with no significant deterioration in the segmental features of speech. One year after implantation 60% of the implant users showed considerable improvement in loudness control, 53% showed a considerable improvement in voice quality and 40% showed a considerable improvement in pitch control and intonation patterns.

In this study we will evaluate the effect of cochlear implantation with the Nucleus 22 implant on speech production of post-lingually deafened subjects using perceptual judgements. Our previous studies using several objective measurements already showed improvements of speech production in these subjects. The first study was directed at the effect of cochlear implantation on vowel production (Langereis *et al.*, 1997a). After implantation we found: an increase in the range of frequencies covered by F_1 and F_2 of eleven vowels; a decrease in the deviation of F_1 and F_2 from the norm frequencies as measured by Pols (1977) for male speakers and by Van Nierop *et al.* (1973) for the female speakers; a decrease in the variability in both formant frequencies and an increase in the clustering rate, defined as the ratio of the between-vowel variance of F_1 and F_2 and the within-vowel variance of three tokens of the same vowel. This increase in clustering rate implies an improvement in the ability to make phonological contrasts. In summary, the study on vowel production showed that post-lingually deafened subjects can improve their vowel production after implantation. Our second study concerned the effect of cochlear implantation on vowel intelligibility of post-lingually deafened subjects using a panel of listeners (Langereis *et al.*, 1997c submitted). This study showed that vowel intelligibility in background noise increased after implantation.

Members of the listener panel used both F_1 and F_2 to identify the vowels. In addition to the measurements in noise, vowel intelligibility of seven poorly speaking subjects was measured in a quiet background. Twelve months post-implantation we found an increase in the vowel intelligibility scores for this subgroup. Finally, this study showed for all subjects together the strongest correlations between the vowel intelligibility scores and the frequency range of F_2 and the deviation of F_2 from the norm values. The third study based on objective measurements was directed at the effect of cochlear implantation on the voice fundamental frequency of the utterances of the same subjects (Langereis *et al.* 1997b). The results of this study showed that when deviations in mean f_0 were present pre-implantation, f_0 was too high compared to the normal mean f_0 of normal-hearing subjects derived from Tielen (1992). Post-implantation, with the implant switched on, we found that abnormally high f_0 values pre-implantation changed toward the norm values. In addition, we found post-implantation that the range over which f_0 varied, the f_0 sway, improved for most subjects with the pre-implantation f_0 sway outside the normal range. In summary, we found marked improvements in the objective measurements of speech production.

The present study, bearing in mind the improvements found in the previous studies, addresses the following questions:

1. What is the effect of cochlear implantation on speech production of these twenty subjects, using perceptual judgements of a large panel of speech therapists?
2. What is the relationship between the judgements of the speech therapists and the outcome of the previous objective measurements?

6.2 Methods

6.2.1 Subjects

Twenty post-lingually deafened Dutch subjects (twelve females and eight males) participated in the experiment. The duration of deafness varied from 1 to 47 years (mean: 14.5 years) and the age of the subjects varied from 28 to 68 years (mean: 45.6 years). All subjects received the Nucleus 22 cochlear implant. Seventeen subjects used the MSP processor and three subjects the WSP-version.

After implantation the subjects received only auditory training, no explicit speech therapy was given. Table 1 provides additional information about the subjects.

6.2.2 Materials

For all subjects speech recordings were made before implantation and at three and twelve months post-implantation with the implant switched on and off. In the implant-off condition the subjects were asked to turn off the implant half an hour before the recordings. The order of the on- and off-conditions was counterbalanced across subjects.

The speech material consisted of a sample of conversational speech when interacting with the investigator during at least two minutes. The subjects responded to open questions about their hobbies, their home, the area where they live, their work and their holidays. The subject was sitting in a chair with the microphone (Sennheiser, MD 421 HL) at a distance of 30 cm. Recordings were made with a high quality Revox A77 taperecorder (bandwidth 20 kHz) in a sound-treated room.

A sample of fourty seconds of each conversation was selected on the basis of a minimal contribution of the investigator to the conversation. This sample was repeated six times to obtain a stimulus of four minutes, providing sufficient time for the listeners to complete all judgements (Huiskamp, 1990).

All stimuli were adjusted to the same level on the tape recorder's VU meter in order to obtain comparable intensity levels across subjects and conditions. Two tapes were constructed: one tape with the stimuli of ten female subjects and a second tape with two female and eight male subjects. The stimuli of the two female and eight male subjects on the second tape were grouped and the listeners were informed about the gender of the subjects in order to minimize female/male differences as a source of variance.

We reduced possible effects of order of presentation by alternating the five speech conditions of the subjects in the following way: the original presentation of speech conditions was revolved (pre-implantation and post-implantation with the implant switched on and off), resulting in five different sequences of presentation. In addition, these five sequences were presented in the reversed order, yielding together ten orders of presentation. Furthermore, we used one stimulus to familiarize the listeners with the rating procedure.

Finally, we added a repetition of the first stimulus at the end of the tape for estimation of the intra-listener reliability.

Table 1. Subject and implant characteristics ordered according to gender and duration of deafness.

	gender	age	etiology	duration of deafness in years	number of active electrodes 3m	number of active electrodes 12m	mean dynamic range (dB) 3m	mean dynamic range (dB) 12m	stimulus strategy 3m	stimulus strategy 12m	CVC phoneme score (%) 3m	CVC phoneme score (%) 12m
1	m	29	meningitis	1	22	21	8.3	13.2	$f_0/F_1/F_2$	$f_0/F_1/F_2$	54.0	47.6
2	m	64	progressive	1	19	18	7.0	10.2	mpeak	mpeak	55.9	40.7
3	m	51	otosclerosis	3	22	22	5.3	4.7	mpeak	mpeak	6.9	27.9
4	m	28	meningitis	9	20	20	3.3	4.7	mpeak	mpeak	19.0	28.5
5	m	29	meningitis	12	22	22	8.0	8.0	mpeak	mpeak	27.4	37.5
6	m	32	meningitis	22	11	11	9.9	9.5	$f_0/F_1/F_2$	f_0/F_2	11.3	9.2
7	m	33	meningitis	24	22	22	10.3	13.9	$f_0/F_1/F_2$	$f_0/F_1/F_2$	4.3	27.6
8	m	51	meningitis	40	22	22	4.9	5.6	mpeak	mpeak	0.0	21.5
9	f	65	otosclerosis	2	16	16	4.9	4.3	mpeak	mpeak	13.0	23.8
10	f	52	meningitis	3	20	15	7.6	7.4	mpeak	mpeak	28.5	28.8
11	f	40	otitis	4	21	16	4.4	1.2	mpeak	mpeak	13.2	27.1
12	f	37	progressive	5	18	18	2.8	2.1	mpeak	mpeak	32.5	35.9
13	f	33	unknown	5	18	14	5.3	3.5	mpeak	$f_0/F_1/F_2$	2.7	3.5
14	f	49	otosclerosis	6	20	20	3.5	3.5	mpeak	mpeak	35.1	30.0
15	f	54	unknown	7	22	22	4.3	4.3	mpeak	mpeak	45.8	43.1
16	f	68	unknown	8	22	20	4.5	2.8	mpeak	$f_0/F_1/F_2$	22.6	22.3
17	f	40	progressive	11	20	20	3.9	3.0	mpeak	mpeak	36.0	41.5
18	f	43	otitis	39	17	14	0.8	1.2	mpeak	mpeak	5.5	10.4
19	f	56	unknown	41	16	12	1.6	2.8	mpeak	mpeak	9.4	13.0
20	f	57	meningitis	47	20	20	2.3	3.2	mpeak	mpeak	2.7	11.8

All subjects have an MSP, except for subject 1,6 and 7, who have an WSP processor.

6.2.3 Listeners

Fifty-four third-grade female students of speech and language pathology from two Universities voluntarily served as listeners. One group consisted of 19 listeners, the other group of 35. We selected the advanced students rather than professionally active speech pathologists, because the latter may differ considerably in their experience with voice disorders and speech of the deaf and consequently in their personal reference system (Kreiman *et al.*,1992, 1993). The group of 19 listeners was presented with the tape of ten female subjects; the group of 35 listeners with the second tape of two female and eight male subjects. All listeners were unfamiliar with the hearing status of the subjects.

6.2.4 Procedure

At the beginning of the experiment, the listeners received a printed instruction form explaining the whole procedure. They were seated in a quiet class room. The recorded stimuli were presented at a comfortable level via loudspeakers. In order to avoid fatigue effects the experiment in both listenergroups was divided in two sessions of two hours each including a break of fifteen minutes.

The speech of all subjects was rated on 21 questions, using equal-appearing interval (EAI) scales. Fifteen questions were rated on a 5-point scale, six on a 9-point scale (Appendix I). For the 5-point scale the normative production corresponded to 5, for the 9-point scale it also corresponded to 5 with deviations in one direction toward the rating of 1 and deviations in the other direction toward the rating of 9. In order to be able to combine the results for statistical analysis the 9-point scale was folded so that the ratings 1 and 9 both received the value 1 expressing the most deviant production and the score 5 expressing the normative production.

6.3 Results

6.3.1 Mean ratings per question

The mean ratings per question across all subjects in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off are presented in Fig. 1.

The effect of cochlear implantation on these mean ratings across all twenty subjects was studied using analysis of variance (ANOVA, CSS Statistica). Because speech production of the subjects was evaluated by two different groups of listeners resulting in an incomplete design, we excluded the listener factor from the first

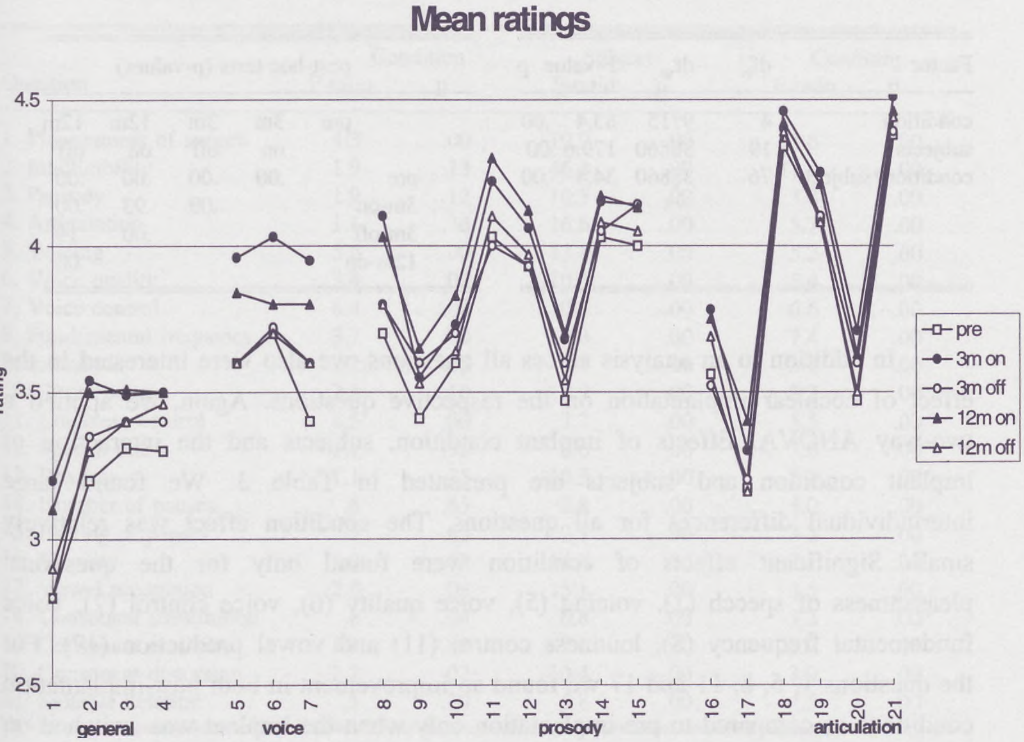

Fig. 1. Mean ratings for the 21 questions of Appendix I in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off. Results for twenty subjects presented to both groups of listeners.

analysis. The results of a two-way analysis of variance and subsequent post-hoc tests (Tukey's Honestly Significant Difference test, HSD) across all 21 questions are presented in Table 2. The two main effects, implant condition and subject, are highly significant ($p<0.00$). Post-hoc analysis for the factor implant condition revealed a significant improvement in the ratings post-implantation as compared to pre-implantation ($p<0.00$). Also, Table 2 shows significant differences between the implant switched on and off conditions ($p<0.00$). Both, at three and twelve months post-implantation higher ratings were noted for the implant switched-on conditions. However, Table 2 shows no significant difference between the three and twelve months condition when either the implant was switched on or off. Finally, we found a significant interaction between implant condition and subjects ($p<0.00$).

Table 2. Results from a two-way ANOVA, giving factors, degrees of freedom (df), F-ratios and p-values. Subsequent post-hoc test results (Tukey's HSD) are given for the five different conditions: pre-implantation (pre) and three (3m) and twelve months (12m) post-implantation with the implant switched on and off. Speech materials from 20 subjects presented to all listeners.

Factor	df_b	df_w	F-value	p
condition	4	9715	83.4	.00
subjects	19	38860	179.6	.00
condition*subject	76	38860	34.4	.00

post-hoc tests (p-values)	pre	3m on	3m off	12m on	12m off
pre		.00	.00	.00	.00
3m-on			.00	.93	.00
3m-off				.00	.19
12m-on					.00

In addition to an analysis across all questions, we also were interested in the effect of cochlear implantation on the respective questions. Again, we applied a two-way ANOVA. Effects of implant condition, subjects and the interaction of implant condition and subjects are presented in Table 3. We found large interindividual differences for all questions. The condition effect was relatively small. Significant effects of condition were found only for the questions: pleasantness of speech (1), voicing (5), voice quality (6), voice control (7), voice fundamental frequency (8), loudness control (11) and vowel production (17). For the questions 1, 5, 8, 11 and 17 we found an improvement in both post-implantation conditions as compared to pre-implantation only when the implant was switched on ($p<0.01$). In addition, post-implantation, we noted significantly higher ratings for these questions in the implant switched-on condition than in the switched-off condition ($p<0.01$). For question 6 we found an improvement only at three months post-implantation with the implant switched on ($p<0.01$). For question 7 we found significantly higher ratings at three and twelve months post-implantation with both the implant switched on and off as compared to pre-implantation ($p<0.01$). Also for this question significantly better ratings were found with the implant switched on than with the implant switched off ($p<0.01$). Finally, we noted a significant interaction between subjects and condition for all questions, implying different effects of implantation on these speech production aspects for individual subjects.

Table 3. Results from a two-way ANOVA. F-ratios and p-values of condition-, subject- and condition/subject (Con/Subj) effects are presented for the individual questions.

Question	Condition F-ratio	Condition p	Subject F-ratio	Subject p	Con/Subj F-ratio	Con/Subj p
1. Pleasantness of speech	4.3	.00	19.9	.00	11.6	.00
2. Intelligibility	1.9	.13	46.4	.00	11.9	.00
3. Prosody	1.9	.12	10.5	.00	3.8	.00
4. Articulation	1.1	.36	16.6	.00	5.7	.00
5. Voicing	5.6	.00	13.8	.00	5.2	.00
6. Voice quality	3.4	.01	10.3	.00	5.4	.00
7. Voice control	6.4	.00	10.7	.00	6.6	.00
8. Fundamental frequency	3.7	.00	33.8	.00	7.4	.00
9. Intonation	2.2	.08	9.1	.00	3.7	.00
10. Stress pattern	2.1	.10	12.9	.00	3.7	.00
11. Loudness control	4.5	.00	7.7	.00	5.5	.00
12. Speech rate	1.1	.35	6.6	.00	5.0	.00
13. Rhythm	1.1	.35	10.3	.00	5.1	.00
14. Number of pauses	.6	.65	2.8	.00	3.0	.00
15. Placing of pauses	.7	.62	2.7	.00	3.2	.00
16. Nasality	1.6	.19	14.8	.00	7.1	.00
17. Vowel production	2.9	.03	15.1	.00	3.5	.00
18. Consonant substitution	.6	.68	6.8	.00	3.3	.00
19. Consonant omission	1.1	.35	7.0	.00	3.7	.00
20. Consonant distorsion	2.2	.07	10.4	.00	3.9	.00
21. Syllable deletion	.5	.70	5.8	.00	4.5	.00

Following the above analysis, we applied ANOVA to the results of both groups of subjects separately. This approach enabled us to include listeners as a factor, using a three-way ANOVA (random factors: listeners and subjects; fixed factor: implant condition). In this analysis we used the results of only those listeners who completed both sessions of the experiment; i.e. 11 of the group of 19 listeners and 25 of the group of 35 listeners. For the group of ten female subjects judged by the group of 11 listeners we noted a significant effect of implant condition (Table 4) on the ratings of the questions: 1,2,5,7,8,11 and 17, pertaining to voice aspects, intelligibility and vowel production. For the group of two female and eight male subjects judged by 25 listeners we found significant effects on only the ratings of the questions 5,6 and 7, pertaining to voicing ($p<0.05$). Thus, we found most effects of cochlear implantation on speech quality for the group of ten female subjects. For both groups of subjects we found significant main effects of subjects and listeners for all questions ($p<0.01$). In addition, we found a significant interaction effect between subjects and listeners, implying that listeners varied in their judgements of subjects ($p<0.01$).

Table 4. F-ratios and p-values for all 21 questions concerning the condition effect in a three-way ANOVA for both subject and listener groups separately.

	11 listeners (from 19 listeners) 10 female subjects		25 listeners (from 35 listeners) 2 female and 8 male subjects	
Question	F	p	F	p
1	5.7	.00	1.5	.23
2	3.4	.02	.7	.58
3	1.7	.17	1.1	.38
4	1.7	.17	.3	.86
5	4.7	.004	2.8	.04
6	2.3	.08	2.9	.03
7	4.7	.004	2.9	.04
8	2.7	.04	.7	.61
9	1.9	.13	.8	.55
10	1.5	.22	1.1	.38
11	3.2	.02	1.2	.31
12	.9	.54	.9	.52
13	1.2	.33	1.1	.37
14	.7	.60	1.1	.38
15	.8	.52	1.6	.20
16	1.4	.25	1.3	.29
17	2.6	.05	1.3	.31
18	.1	.96	.7	.57
19	.4	.81	2.0	.12
20	1.6	.18	1.4	.24
21	.8	.55	1.2	.34

6.3.2 Principal components of the questions

In order to assess the number of independent dimensions in the items of the questionnaire we applied a principal components analysis (followed by a varimax rotation) to the specific questions 5-21. The factor loadings revealed by this analysis performed on all data for the five conditions together are presented in Table 5. We found three to four important factors (we found similar factors for the five conditions separately). The first factor is marked by high loadings on the segmental questions (articulation), the second factor is marked by high loadings on voicing aspects, the third factor by questions involving speech rate and the fourth factor by questions involving stress pattern. The groups of questions representing the four different factors and their interpretations are presented in Table 6. Two questions (15,16) are not included in this table, because these questions load about equally on two factors. Question 15 (placing of pauses) loads on factor 3 and 4, which are both prosodic factors. Question 16 (nasality) loads on factor 1 and 2, suggesting that nasality is correlated to both articulation and voicing aspects.

Table 5. Factor loadings derived from a principal component analysis.

	Factor 1	Factor 2	Factor 3	Factor 4
Voice				
5. Voicing	.209	.738*	.041	.029
6. Voice quality	.080	.753*	.036	-.050
7. Voice control	.080	.778*	.023	.259
Prosody				
8. Fundamental frequency	.067	.629*	.127	.198
9. Intonation	.175	.151	.126	.655*
10. Stress pattern	.225	.166	.069	.789*
11. Loudness control	.084	.587	.460	.430
12. Speech rate	.107	.105	.785*	.046
13. Rhythm	.184	.093	.127	.715*
14. Number of pauses	.103	.057	.843*	.161
15. Placing of pauses	.146	.076	.552	.503
Articulation				
16. Nasality	.422	.392	.094	.034
17. Vowel production	.669*	.201	.041	.291
18. Consonant substitution	.761*	.045	.022	.159
19. Consonant omission	.826*	.043	.132	.105
20. Consonant distorsion	.742*	.162	.109	.212
21. Syllabe deletion	.738*	.104	.089	.087
Expl. variance in %	32	11	10	7
*: loadings >0.600				

Table 6. The items of the subjective questionnaire representing the four different factors, their interpretation and the percentage explained variance revealed by the principal components analysis.

Factor	Interpretation	Questions	var (%)
1	Segmental aspects	17,18,19,20,21	32
2	Voice aspects	5,6,7,8,(11)	11
3	Temporal aspects	12,14	10
4	Intonation	9,10,13	7

Next, we examined the relationship between the questions concerning the general impression: pleasantness of speech (1), intelligibility (2), prosody (3) and articulation (4) and the four principal components. Table 7 shows the correlation coefficients for the conditions pre-implantation and post-implantation (three and twelve months together) with the implant switched on and off. For the articulation factor we found the strongest correlations with the general questions involving articulation (4) and intelligibility (2) ($p<0.01$). Apparently, the segmental questions are self-evident for the listeners. For the factor voicing we found the strongest correlations with the question concerning pleasantness of speech ($p<0.01$). For the factors speech rate and stress pattern the highest correlations were seen with the prosody question ($p<0.01$). However, stronger correlations were seen for the factor stress pattern, suggesting that listeners connect prosody with stress pattern rather than with speech rate. The general items 1-4 of the questionnaire did not address the quality of voicing. This principal components analysis shows that voicing is an important factor. It correlates from 0.70 to 0.81 with question 1: pleasantness of speech. However, pleasantness of speech shows the highest correlation with factor 1: articulation. Except for the factor voicing stronger correlations were found pre-implantation as compared to post-implantation with both the implant switched on and off. In addition, we found higher correlations for the factors: voicing, speech rate and stress pattern with the implant switched on as compared to the implant switched-off condition.

Table 7. Correlations between the four respective factors and the general questions.

	factor1	factor2	factor3	factor4
pre-implantation				
1. Pleasantness of speech	.90**	.70**	.77**	.86**
2. Intelligibility	.90**	.32	.71**	.75**
3. Prosody	.85**	.54*	.80**	.96**
4. Articulation	.96**	.45*	.71**	.78**
post-implantation (3 and 12 months) with the implant switched on				
1. Pleasantness of speech	.87**	.81**	.70**	.86**
2. Intelligibility	.89**	.66**	.62**	.82**
3. Prosody	.79**	.67**	.73**	.91**
4. Articulation	.92**	.65**	.60**	.78**
post-implantation (3 and 12 months) with the implant switched off				
1. Pleasantness of speech	.83**	.75**	.61**	.76**
2. Intelligibility	.91**	.45*	.63**	.76**
3. Prosody	.82**	.58**	.63**	.87**
4. Articulation	.93**	.41*	.58**	.69**

*: p<0.05; **: p<0.01

6.3.3. Mean ratings per principal component and related general question

Fig. 2 shows the mean ratings of the groups of questions representing the four different factors in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off together with the mean ratings of the related general questions 1-4 (data from Fig. 1). We found significantly higher mean ratings for the groups of questions representing the voicing factor at three and twelve months post-implantation ($p<0.01$) as compared to pre-implantation. Switching off the implant resulted in lower values for this factor ($p<0.01$). For the groups of questions representing the factors articulation and stress pattern the main effect of condition ($p=0.08$) just failed to reach the significance level of $p=0.05$. No significant condition effect was found for the factor speech rate. Also, this figure shows that the general questions resulted in lower ratings as compared to the mean ratings of the groups of questions representing the factors. We mostly found similar F-ratios for the mean ratings of the groups of questions representing the factors and the general questions. This suggests that we can limit ourselves to the general questions. For the factor voicing, however, we

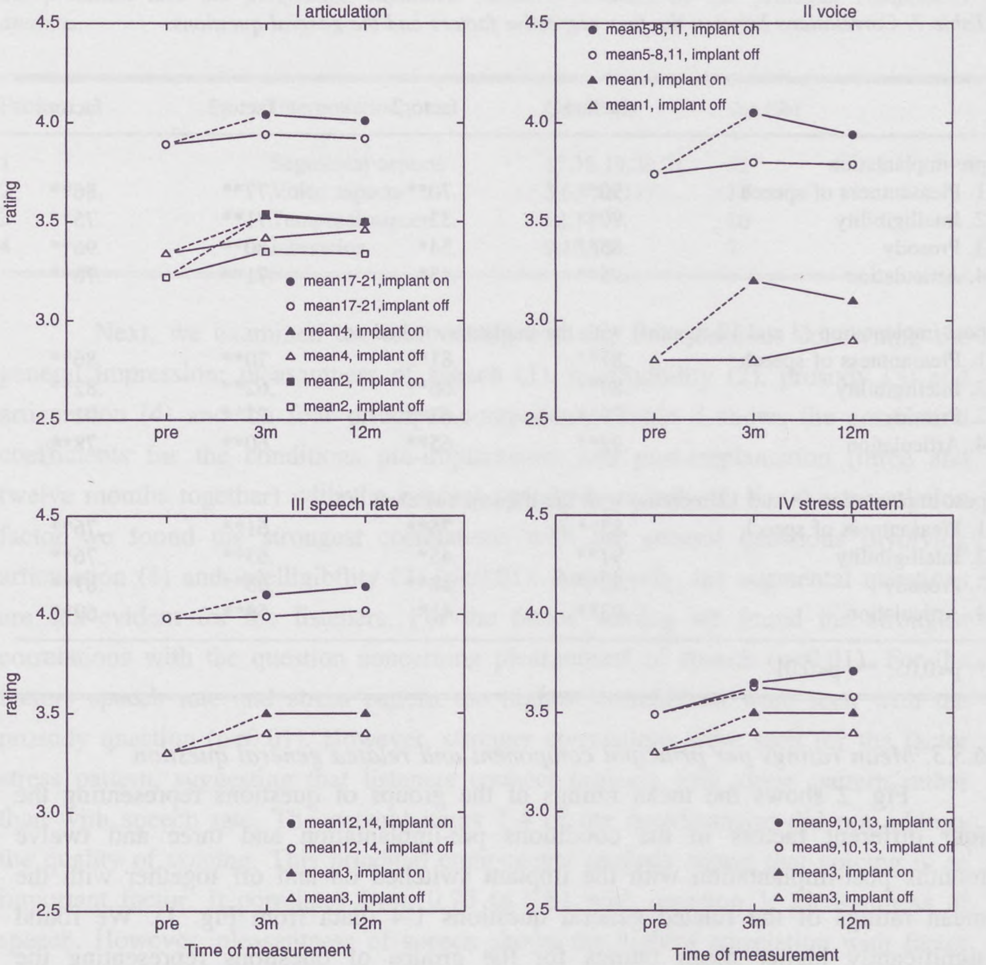

Fig. 2. The mean ratings of the groups of questions representing the four different factors (articulation, voicing, speech rate and stress pattern) in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on, together with the mean ratings of the related general questions 1-4 (data from Fig. 1).

did find a higher F-ratio as compared to the F-ratio for the related question, of pleasantness of speech production. The related question is mainly related to articulation, implying that a general question pertaining to voicing should be added.

6.3.4 Effect of duration of deafness

In order to examine whether duration of deafness was an important variable we classified our subjects in two groups with duration of deafness less and more than ten years, respectively. Applying a three-way ANOVA (fixed factors: implant condition, group of subjects and speech factors) we found a significant effect of duration of deafness ($p<0.01$). The results are presented in Fig. 3. This figure shows that pre-implantation the ratings for the group of subjects with a hearing loss of less than 10 years were higher than those for the group of subjects with a hearing loss

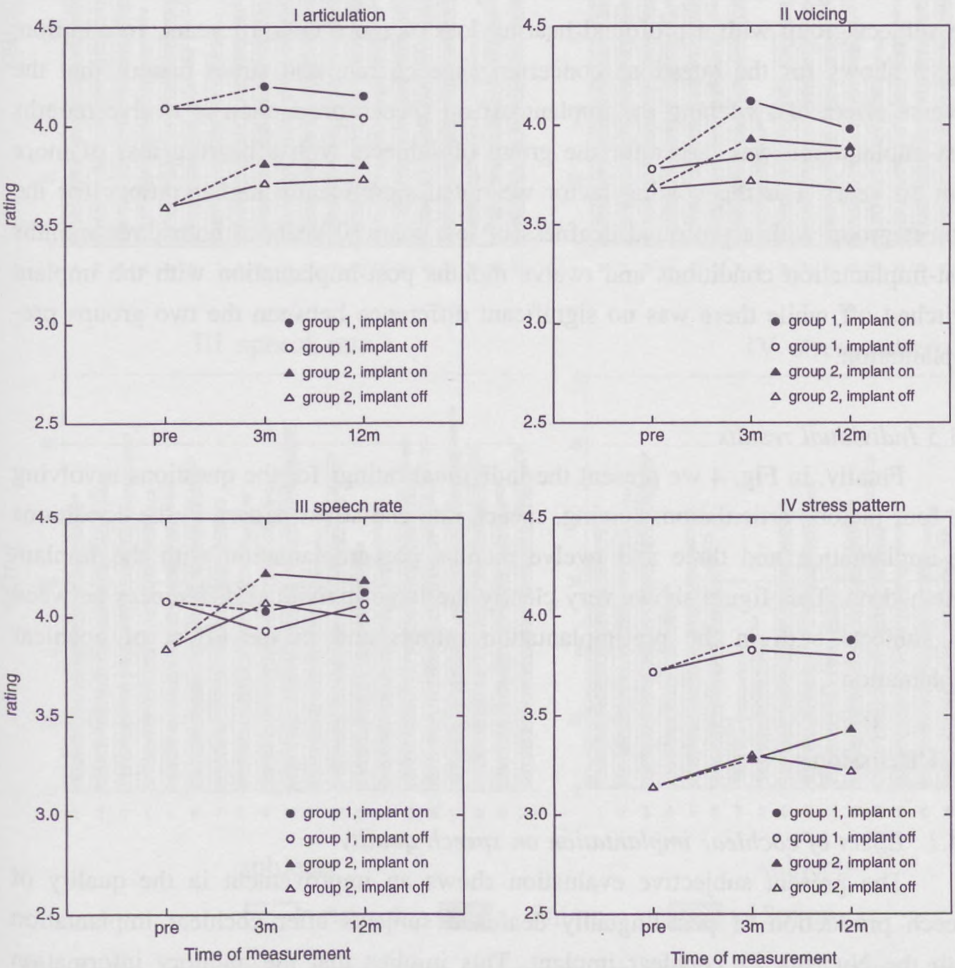

Fig. 3. The mean ratings of the groups of questions representing the four different factors (articulation, voicing, speech rate and stress pattern) in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on and off for two groups of subjects selected on the basis of duration of deafness: 1= duration less than 10 years; 2= duration more than 10 years.

of more than 10 years for the questions involving the factors: articulation and stress pattern; the small difference found for the factor voicing was insignificant.

Three and twelve months post-implantation with the implant switched on and off we found higher scores for the group of subjects with a profound hearing loss of less than 10 years for the questions concerning the articulation and the stress pattern factor. For the speech rate factor we found no significant differences between the two subject groups in the post-implantation conditions, except for the condition three months post-implantation with the implant switched on with higher scores for the subject group with a profound hearing loss of more than 10 years. In addition, Fig. 3 shows for the questions concerning speech rate and stress pattern that the adverse effect of switching the implant off on speech production at twelve months post-implantation was larger for the group of subjects with a hearing loss of more than 10 years. For the voicing factor we noted significantly higher ratings for the subject group with a profound deafness of less than 10 years at both three months post-implantation conditions and twelve months post-implantation with the implant switched off while there was no significant difference between the two groups pre-implantation.

6.3.5 Individual results

Finally, in Fig. 4 we present the individual ratings for the questions involving the four factors: articulation, voicing, speech rate and stress pattern in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on. This figure shows very clearly the large individual differences between the subjects both in the pre-implantation ratings and in the effect of cochlear implantation.

6.4 Discussion

6.4.1 Effect of cochlear implantation on speech quality

The present subjective evaluation shows an improvement in the quality of speech production of post-lingually deafened subjects after cochlear implantation with the Nucleus 22 cochlear implant. This implies that the auditory information from the implant may indeed be used to improve speech production. In addition, we found significant differences between the implant switched-on and off conditions. Both at three and twelve months post-implantation higher ratings were found for the implant switched-on conditions, implying that even after twelve months subjects still use the auditory information to control their speech production.

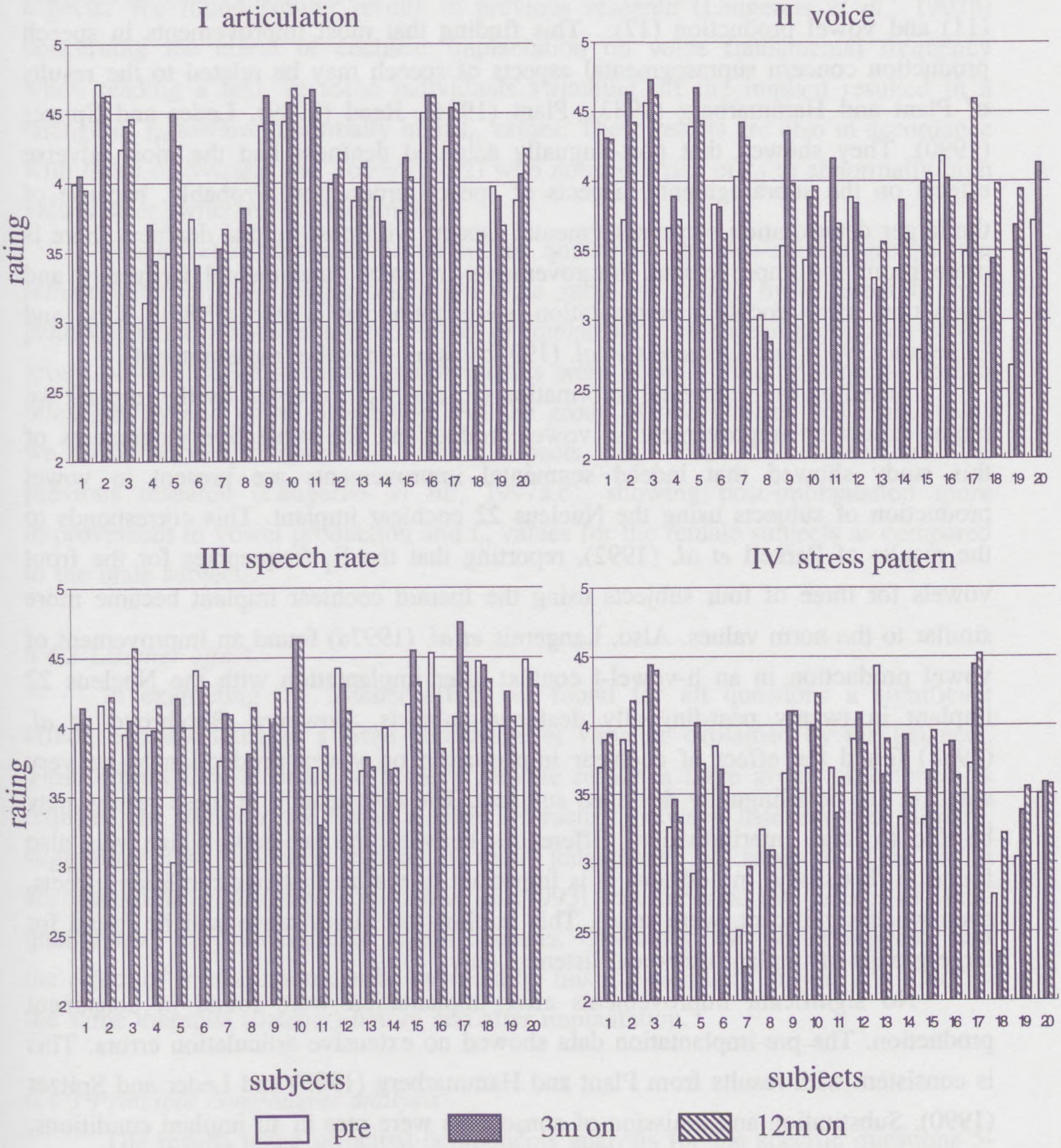

Fig. 4. The mean ratings of the groups of questions representing the four different factors (articulation, voicing, speech rate and stress pattern) in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on for the twenty subjects.

The largest improvements of cochlear implantation across all subjects were found for the questions: pleasantness of speech production (1), voicing (5), voice quality (6), voice control (7), voice fundamental frequency (8), control of loudness (11) and vowel production (17). This finding that most improvements in speech production concern suprasegmental aspects of speech may be related to the results of Plant and Hammarberg (1983), Plant (1984), Read (1989), Leder and Spitzer (1990). They showed that post-lingually acquired deafness had the most adverse effects on the suprasegmental aspects of speech production. Probably, because of the larger deterioration of suprasegmental aspects with post-lingual deafness there is more room for improvement. Improvements in voice fundamental frequency and intonation after cochlear implantation were found by Oster (1987), Kirk and Edgerton (1983) and Langereis *et al.* (1997b) using objective measurements.

Based on the segmental information (F_1 and F_2) conveyed by the implant we might expect an improvement in vowel production. The subjective judgements of this study showed that indeed segmental improvements are present in vowel production of subjects using the Nucleus 22 cochlear implant. This corresponds to the results of Perkell *et al.* (1992), reporting that the F_2 frequencies for the front vowels for three of four subjects using the Ineraid cochlear implant became more similar to the norm values. Also, Langereis *et al.* (1997a) found an improvement of vowel production in an h-vowel-t context after implantation with the Nucleus 22 implant in twenty post-lingually deafened subjects. However, Boothroyd *et al.* (1988) found the effect of cochlear implantation on vowel production to be very small in six post-lingually deafened subjects. The discrepancy in these results may be due to large interindividual differences between the subjects, which was also found in this study. In addition, it is important to realize that our condition effects, even when significant, were small. This implies that significance will be found for large groups of implant users and listeners only.

No significant improvements after implantation were found in consonant production. The pre-implantation data showed no extensive articulation errors. This is consistent with results from Plant and Hammarberg (1983) and Leder and Spitzer (1990). Substitution and omission of consonants were rare in all implant conditions. Distortion of consonants, however, was found more often, considering the lower ratings on this question (20) pre-implantation. Although we found no statistically significant effect on consonant production, it did improve in some individuals after implantation.

Switching off the implant both at three and twelve months often resulted in a deterioration of speech production. The largest effects were found for the voicing aspects. We found similar results in previous research (Langereis *et al.*, 1997b) concerning the effect of cochlear implantation on voice fundamental frequency when reading a text. In some individuals switching off the implant resulted in a change of f_0 toward abnormally high f_0 values. These results are also in accordance with those of Svirsky and Tobey (1992) who noticed a rise of f_0 to abnormally high values after switching off the implant.

The effect of implantation on speech quality for the two subject groups (ten female subjects; two female and eight male subjects) judged by different listener panels separately showed a larger effect of implantation on speech production of the group of ten female subjects. Improvements were seen in voicing aspects, speech intelligibility and vowel production. For the group of two females and eight males we found an improvement in voicing aspects only. This is in agreement with previous research (Langereis *et al.*, 1997a,b), showing post-implantation more improvement in vowel production and f_0 values for the female subjects as compared to the male subjects.

6.4.2 Listener effect

In examining the listener effect we found for all questions a significant effect, corresponding to a large percentage of variance explained by the listeners. This implies that in order to achieve reliable results a large group of listeners is required. In addition, we found a large interaction between listeners and subjects, suggesting that listeners varied in their judgements of subjects. This is in accordance with results of Kreiman *et al.* (1993) who reported that ratings of vocal quality may vary enormously across listeners. Obviously, this result suggests that the effect of implantation can be assessed by this questionnaire only if it is used by the same therapist (listener) before and after implantation.

6.4.3 Principal components analysis

The results using principal components analysis for the specific questions 5-21 showed that four factors are important: articulation, voicing, speech rate and stress pattern. The ratings for the questions involving the articulation factor (17-21) correlated strongly with the ratings for the general questions on articulation and intelligibility. The factor voicing correlated highly with the general question concerning pleasantness of speech production and both the factor stress pattern and speech rate correlated highly with the general question about prosody. However, higher correlations were found between prosody and stress pattern than between prosody and speech rate. This implies that listeners associate prosody with intonational rather than temporal aspects. This is consistent with findings of Huiskamp (1990). For the general questions and the mean ratings of the groups of questions representing the factors we mostly found similar F-ratios. This suggests that the number of questions of the questionnaire may be reduced to the general questions. Interestingly, for the factor voicing we did find a higher F-ratio as compared to the F-ratio of the related question, of pleasantness of speech production. Considering that the question on pleasantness is mainly related to articulation, we conclude that a general question pertaining to voicing should be added.

6.4.4 Classification of subjects according to duration of deafness

After classifying the subjects according to the duration of deafness (less or more than ten years) we found pre-implantation significant differences between these two groups of subjects for the factors: articulation, speech rate and stress pattern. The ratings for the subjects with a profound hearing loss during less than 10 years were better than those for hearing loss over ten years. These results are in accordance with results of Plant and Hammarberg (1983) and Cowie *et al.* (1982). Moreover, the differences in articulation and stress pattern remained after implantation, implying that early implantation may be advised to miminize negative effects of deafness on speech production. However, pre-implantation we found no significant differences between these two groups for the factor voicing. This is in agreement with the objective measurements on f_0 in an earlier study (Langereis *et al.* 1997b).

6.4.5 Relation between subjective and objective measurements

The relationship between the subjective judgements of the students of speech and language pathology and the objective measurements of three previous studies on speech production of the same twenty subjects (Langereis *et al.* 1997a,b,c) is presented in Appendix II. In addition, we studied the relation between both the subjective and objective measurements and the variables: duration of deafness and the consonant-vowel-consonant (CVC) perception scores (Bosman and Smoorenburg, 1995). In summary, the strongest correlations were found between the second formant measurements and the CVC-perception scores, the vowel intelligibility scores and the subjective rating scales. Also, we found significant correlations between the duration of deafness and both the F_2-distance to the norm values and F_2-range, general ratings of speech production and ratings concerning both articulatory aspects and control of loudness.

6.5 Conclusions

Our study shows that cochlear implantation with a Nucleus 22 implant improves the quality of speech production of post-lingually deafened subjects. The largest improvements were seen in the suprasegmental aspects. However, we also found improvements in vowel production. In addition, post-implantation we found significant lower ratings with the implant switched off versus switched on, implying that the auditory information from the implant is used to improve speech production.

This study indicated that subjects with a profound hearing loss during less than ten years had better speech quality than subjects with a profound hearing loss during more than ten years pre-implantation. Moreover, these differences remained post-implantation.

With respect to the relationship between the present judgements of the speech therapists and the outcome of the previous objective measurements we found strong correlations between the second formant measurements and the CVC-perception scores, the vowel intelligibility scores and the subjective rating of segmental aspects, respectively.

Finally, this study showed large interindividual differences between the subjects and in the effect of cochlear implantation on speech quality.

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Appendix I

Subjective questionnaire developed by T. Huiskamp (1990)

General impression:			
1. How does the speech sound?	unpleasant	1-2-3-4-5	pleasant
2. Intelligibility	worse	1-2-3-4-5	good
3. Prosody	worse	1-2-3-4-5	good
4. Articulation	sloppy	1-2-3-4-5-6-7-8-9	over-articulated
Voice:			
5. Voicing	hypotonic	1-2-3-4-5-6-7-8-9	hypertonic
6. Voice quality	hoarse	1-2-3-4-5	clear
7. Voice control	worse	1-2-3-4-5	good
Prosody:			
8. Voice fundamental frequency	too low	1-2-3-4-5-6-7-8-9	too high
9. Intonation	monotonous	1-2-3-4-5-6-7-8-9	too variable
10. Stress pattern	incorrect	1-2-3-4-5	correct
11. Loudness control	worse	1-2-3-4-5	good
12. Speech rate	too slow	1-2-3-4-5-6-7-8-9	too fast
13. Rhythm	staccato	1-2-3-4-5	fluently
14. Number of pauses	too few	1-2-3-4-5-6-7-8-9	too many
15. Placing of pauses	wrong	1-2-3-4-5	good
Articulation:			
16. Nasality	deviating	1-2-3-4-5	normal
17. Vowel production	distorted	1-2-3-4-5	good
18. Consonant: - substitution	often	1-2-3-4-5	never
19. - omission	often	1-2-3-4-5	never
20. - distortion	often	1-2-3-4-5	never
21. Syllable deletion	often	1-2-3-4-5	never

Appendix II

In this appendix we present the relationship between the subjective measurements of the present study and the results of three previous studies on speech production for the same twenty subjects (Langereis *et al.* 1997 a,b,c). In order to quantify the relationship between the two types of studies we calculated the coefficient of the correlation between the subjective ratings of the present study and the objective measurements of the previous ones. Table 8 presents these correlation coefficients for the conditions pre-implantation and three and twelve months post-implantation with the implant switched on across all twenty subjects. (The results of the vowel identification experiment in a quiet background are presented for seven subjects.) In all three conditions we found the highest correlations between the objectively measured frequency range of F_2 and the segmental rating scores (17-21) together with the general questions on pleasantness of speech (1), intelligibility (2) and articulation (4). Moreover, in one of the previous studies (Langereis *et al*, 1997c) the frequency range of F_2 was already found to correlate significantly with the vowel intelligibility scores in noise. Similar results were found for the vowel intelligibility scores in quiet. We also found significant correlations between the frequency range of F_1 and the subjective ratings concerning articulatory aspects. For the deviations of F_2 from the norm values we also found significant correlations with the vowel intelligibility scores and the subjective ratings of segmental aspects. Table 8 shows weaker correlations between the subjective ratings and the clustering rate for both formants, the variability in both formants, and the deviation of F_1 values from the norm frequencies. For voice fundamental frequency we found significant correlations between the objective measurements on mean f_0 and the subjective rating scale (8) in all conditions. The principal components scores did not show higher correlation coefficients (not shown).

In addition, we calculated the correlation coefficients between both the subjective and objective measurements and the variables: duration of deafness and the consonant-vowel-consonant (CVC) perception scores. Pre-implantation, we found significant correlations between the duration of deafness and both the F_2-distance and F_2-range, general ratings of speech production and ratings concerning both articulatory aspects and control of loudness. Interestingly, the correlation between the duration of deafness and the distance of F_2 to the norm values, rating of vowel quality and consonant substitution is weaker twelve months post-implantation, suggesting that the difference in speech production between subjects with longer duration of deafness and subjects with shorter durations of deafness becomes smaller. However, the contrary is suggested by higher correlations post-implantation for the variables: F_2-range, vowel intelligibility scores in noise and intonational aspects (both objective and subjective). This would mean that the largest improvements post-implantation are found in speech production of the initially better speakers.

Finally, post-implantation we found significant correlations between the CVC-perception scores and the objective measurements of the distances of F_1 and F_2 to the norm frequencies and the frequency range of F_2, the vowel identification scores, voice fundamental frequency and some prosodic aspects concerning stress pattern and control of loudness. In summary, the highest correlations were found between the second formant frequency measurements and the CVC-perception scores, the vowel intelligibility scores and the subjective rating scales.

Table 8: Pearson product-moment correlation coefficients for the relationship between the subjective rating scores of the present study and the objective measurements of previous studies and the duration of deafness (length) and CVC-perception scores (CVC) in the conditions pre-implantation and three and twelve months post-implantation with the implant switched on. The following aspects of the previous studies are considered: 1) Measurements on vowel quality (Langereis et al. 1997): the range of frequencies covered by the F_1 and F_2 of the eleven vowels (F_1-range, F_2-range), the deviation of F_1 and F_2 from the norm frequencies as measured by Pols (1977) for male speakers and by Van Nierop (1973) for female speakers (F_1-dist, F_2-dist), the variability in both formant frequencies (F_1-var, F_2-var) and the clustering rate for both formant frequencies (F_1-CR, F_2-CR). 2) Vowel intelligibility measurements: vowel identification scores in noise for all twenty subjects (V-IDn) and vowel intelligibility scores in quiet for seven poorly performing subjects (V-IDq). 3) Measurements on voice fundamental frequency: mean f_0 and the range over which f_0 varied (f_0-sway). 4) the present subjective ratings of speech production.

Pre-implantation

	LENGTH	F1-DIST	F2-DIST	F1-RANGE	F2-RANGE	F1-VAR	F2-VAR	F1-CR	F2-CR	V-IDn	V-IDq	MEAN-f_0	f_0-SWAY
LENGTH	1												
F1-DIST	.38	1											
F2-DIST	.56**	.28	1										
F1-RANGE	-.38	-.25	-.29	1									
F2-RANGE	-.54*	-.17	-.73**	.55*	1								
F1-VAR	.40	.03	.51*	.04	.01	1							
F2-VAR	.03	.11	.06	-.07	.28	.46*	1						
F1-CR	-.29	-.05	-.26	.54*	.06	-.49*	-.25	1					
F2-CR	-.36	-.18	-.31	.50*	.27	-.30	-.76**	.26	1				
V-IDn	-.40	-.44	-.46*	.48*	.62**	-.16	.05	.10	.31	1			
V-IDq	-.39	.50	-.72	.54	.60	-.67	-.70	.85*	.94**	.18	1		
MEAN-f_0	.09	.07	.59**	-.14	-.31	.35	.13	-.10	-.26	-.34	.06	1	
f_0-SWAY	.36	-.16	.10	.10	.08	.24	.06	-.12	-.10	.07	-.05	.03	1
Q1	-.45*	-.18	-.56**	.44	.51*	-.10	-.25	.31	.47*	.11	.43	-.45*	-.08
Q2	-.50*	-.19	-.40	.66**	.70**	.12	-.01	.18	.47*	.36	.48	-.26	.06
Q3	-.55*	-.20	-.35	.43	.37	-.10	-.19	.38	.43	.06	.36	-.19	-.23
Q4	-.55*	-.24	-.48*	.61**	.62**	-.04	-.11	.27	.48*	.27	.49	-.32	.11
Q5	-.31	-.18	-.71**	.10	.22	-.56**	-.35	.39	.29	.26	.55	-.63**	-.19
Q6	.11	.03	-.21	-.13	-.18	-.36	-.18	.34	-.08	.25	-.41	-.35	-.17
Q7	-.30	.04	-.32	.09	-.00	-.35	-.13	.45*	.03	.03	.02	-.32	-.51*
Q8	-.43	-.28	-.58**	.22	.22	-.52*	-.32	.39	.44	.44	-.28	-.78**	-.38
Q9	-.39	-.18	-.03	.40	.04	-.09	-.16	.43	.28	-.04	.12	.10	-.31
Q10	-.60**	-.23	-.39	.32	.29	.19	-.19	.33	.36	-.06	.48	-.14	-.33
Q11	-.53*	-.27	-.43	-.05	-.00	-.50*	-.25	.44	.07	-.04	.09	-.25	-.44
Q12	.14	.14	.20	-.12	.00	.16	.10	-.11	.04	-.01	-.63	-.27	-.03
Q13	-.49*	-.12	-.13	.24	.12	-.06	-.13	.30	.20	-.32	.44	.14	-.32
Q14	-.01	.03	-.07	.23	.26	.20	.01	.04	.25	.00	-.04	-.40	-.08
Q15	-.11	-.10	-.12	.35	.21	.17	-.19	.10	.41	-.05	.31	-.18	-.22
Q16	-.00	-.20	-.29	.27	.25	.15	-.25	.01	.27	-.00	.14	-.28	.35
Q17	-.51*	-.33	-.52*	.57**	.63**	.06	-.23	.04	.58**	.27	.75	-.27	.05
Q18	-.58**	-.17	-.49*	.56**	.61**	-.03	-.07	.28	.46*	.29	.37	-.29	.10
Q19	-.38	-.32	-.37	.66**	.49*	.07	-.15	.29	.48*	.17	.34	-.31	.22
Q20	-.38	-.21	-.44	.60**	.62**	.15	-.02	.14	.38	.14	.45	-.29	.22
Q21	-.51*	-.36	-.34	.54*	.53*	.01	.06	.32	.33	.42	-.05	-.16	.15

(Table 8 continued)

3 months post-implantation, implant on

	LENGHT	CVC	F1-DIST	F2-DIST	F1-RANGE	F2-RANGE	F1-VAR	F2-VAR	F1-CR	F2-CR	V-IDn	V-IDq	MEAN-f_0	f_0-SWAY
LENGTH	1													
CVC	-.55**	1												
F1-DIST	-.57**	-.65**	1											
F2-DIST	.52*	-.63**	.26	1										
F1-RANGE	-.42	.14	-.41	-.19	1									
F2-RANGE	-.49*	.52*	-.23	-.75**	.55*	1								
F1-VAR	-.02	.03	.09	.04	.26	.03	1							
F2-VAR	.12	.31	.18	-.05	-.36	-.17	.31	1						
F1-CR	-.31	.09	-.33	-.16	.52*	.37	-.60**	-.55**	1					
F2-CR	-.05	-.06	-.12	-.17	.44	.51*	-.31	-.79**	.63**	1				
V-IDn	-.50*	.53*	-.44	-.58**	.37	.69**	-.30	-.26	.62**	.41	1			
V-IDq	-.36	.01	.51	-.85*	.37	.79*	.08	-.40	.34	.39	.55	1		
MEAN-f_0	.16	-.42	.34	.35	-.33	-.36	-.27	.12	-.19	-.21	-.45*	.05	1	
f_0-SWAY	-.01	.17	.20	-.36	.41	.11	-.23	.24	-.07	-.07	-.04	.41	-.14	1
Q1	-.45*	.42	-.33	-.64**	.74**	.76**	.36	-.13	.26	.38	.48*	.53	-.46*	-.21
Q2	-.46*	.45*	-.27	-.63**	.71**	.86**	.26	-.09	.28	.41	.50*	.62	-.30	-.17
Q3	-.67**	.45*	-.53*	-.45*	.76**	.59**	.22	-.13	.36	.22	.47*	.34	-.18	-.42
Q4	-.50*	.37	-.24	-.63**	.60**	.78**	.09	-.17	.34	.43	.45*	.68	-.15	-.05
Q5	-.40	.25	-.20	-.66**	.44	.52*	.21	-.25	.25	.33	.34	.54	-.61**	.25
Q6	-.07	.01	.11	-.19	-.03	-.01	-.12	-.23	.26	.27	.15	.26	-.25	.15
Q7	-.33	.27	-.24	-.51*	.22	.25	.11	-.12	.17	.14	.25	.14	-.54*	.17
Q8	-.48*	.52*	-.48*	-.49*	.53*	.47*	.02	-.17	.51*	.27	.53*	-.00	-.79**	.16
Q9	-.53*	.42	-.50*	-.29	.69**	.46*	.15	.03	.34	.08	.36	-.36	-.08	-.41
Q10	-.67**	.54*	-.64**	-.60**	.62**	.60**	.08	-.12	.33	.19	.59**	.34	-.30	-.34
Q11	-.63**	.37	-.39	-.56**	.32	.38	-.14	-.18	.39	.26	.30	.11	-.31	.21
Q12	.19	.03	.16	.15	.13	.09	.02	-.00	.24	.21	.11	-.47	-.31	-.03
Q13	-.48*	.32	-.46*	-.43	.50*	.43	.06	.04	.19	.05	.30	-.16	-.03	-.34
Q14	.24	.28	-.01	.02	.12	.15	.07	.27	.12	.03	.22	-.59	-.30	-.08
Q15	-.03	.11	-.16	-.32	.28	.21	-.02	-.16	.19	.18	.34	.12	-.18	-.38
Q16	-.08	-.10	-.08	-.27	.44	.33	.26	-.21	-.01	.29	-.05	.32	-.08	.01
Q17	-.40	.27	-.07	-.54*	.58**	.70**	.35	-.10	.10	.38	.26	.90**	-.09	-.12
Q18	-.54*	.35	-.40	-.60**	.52*	.63**	-.04	-.14	.33	.31	.39	.64	-.02	-.16
Q19	-.58*	.34	-.38	-.63**	.47*	.64**	-.09	-.20	.31	.31	.36	.72	-.03	.07
Q20	-.45	.29	-.25	-.57**	.64**	.73**	.18	-.14	.25	.39	.35	.73	-.07	-.13
Q21	-.70**	.44	-.46*	-.58**	.32	.55*	-.28	-.18	.43	.30	.49*	.14	-.05	.12

(Table 8 continued)

12 months post-implantation, implant on

	LENGTH	CVC	F1-DIST	F2-DIST	F1-RANGE	F2-RANGE	F1-VAR	F2-VAR	F1-CR	F2-CR	V-IDn	V-IDq	MEAN-f_0	f_0-SWAY
LENGTH	1													
CVC	-.57**	1												
F1-DIST	.22	-.59**	1											
F2-DIST	.43	-.70**	.32	1										
F1-RANGE	-.23	.07	-.13	-.12	1									
F2-RANGE	-.62**	.67**	-.25	-.72**	.48*	1								
F1-VAR	.07	-.33	.20	.51*	.18	-.09	1							
F2-VAR	.23	-.32	.08	.68**	.12	-.44	.56*	1						
F1-CR	-.10	.38	-.42	-.36	.28	.20	-.70**	-.32	1					
F2-CR	-.32	.46	-.05	-.66**	-.09	.49*	-.30	-.80**	.16	1				
V-IDn	-.50*	.63**	-.41	-.37	.37	.63**	-.23	-.40	.38	.47*	1			
V-IDq	-.06	.09	.29	-.85*	.56	.80*	-.59	-.80*	.51	.63	.49	1		
MEAN-f_0	.25	-.32	-.05	.02	-.17	-.29	.08	.26	-.21	-.33	-.59**	.22	1	
f_0-SWAY	-.59**	-.33	.15	.10	.13	-.24	-.17	.03	.17	-.30	-.17	.51	-.11	1
Q1	-.43	.34	.12	-.40	.43	.65**	-.01	-.37	.09	.35	.55**	.77*	-.33	-.01
Q2	-.47*	.34	.03	-.49*	.48*	.72**	.06	-.39	.03	.38	.53*	.89*	-.15	-.12
Q3	-.60**	.46*	-.20	-.32	.51*	.57**	.06	-.12	.18	.21	.58**	.30	-.21	-.26
Q4	-.51*	.35	-.00	-.44	.39	.64**	.08	-.30	-.04	.29	.51*	.80*	-.02	-.22
Q5	-.27	.42	.16	-.42	.19	.36	-.26	-.39	.22	.32	.45*	.56	-.52*	.27
Q6	-.07	.29	.04	-.01	.06	-.06	-.42	-.14	.42	.13	.39	-.29	-.34	.05
Q7	-.37	.54*	-.01	-.37	.17	.33	-.42	-.44	.44	.44	.59**	.22	-.72**	.09
Q8	-.50*	.49*	-.19	-.14	.32	.39	-.22	-.14	.35	.18	.68**	-.23	-.67**	-.02
Q9	-.53*	.44	-.20	-.20	.39	.43*	.09	.08	.08	.07	.44	-.09	.00	-.37
Q10	-.59**	.51*	-.21	-.39	.59**	.67**	.03	-.15	.29	.21	.57**	.61	-.25	-.27
Q11	-.49*	.54*	-.05	-.33	.25	.51*	-.23	-.31	.32	.36	.57**	.03	-.56**	-.19
Q12	.02	.15	.01	.31	.14	.07	.34	.39	-.15	-.29	.21	-.73	-.13	-.19
Q13	-.51*	.14	-.06	-.16	.45*	.42	.09	.08	.15	-.01	.08	.20	-.16	-.24
Q14	.23	.11	.20	.15	.13	.08	.15	.25	.06	-.23	.05	-.04	-.13	.14
Q15	-.09	-.05	.40	-.05	.16	.02	-.32	-.13	.27	-.09	-.07	.51	.03	-.02
Q16	-.22	.32	.11	-.33	.18	.44	.03	.01	-.15	.19	.28	.85*	-.06	.03
Q17	-.22	.17	.13	-.40	.34	.59**	-.09	-.46*	.13	.36	.45*	.90**	-.12	-.04
Q18	-.49*	.37	-.13	-.61**	.41	.63**	-.24	-.48*	.29	.48*	.54*	.85*	-.03	-.16
Q19	-.51*	.35	-.16	-.50*	.46*	.59**	.02	-.17	.08	.31	.40	.82*	.04	-.15
Q20	-.41	.24	.12	-.48*	.46*	.68**	.00	-.39	.05	.35	.46*	.87**	-.11	-.08
Q21	-.62**	.66*	-.39	-.63**	.37	.66**	-.17	-.27	.25	.39	.60**	.49	-.02	-.15

* $p<0.05$; ** $p<0.01$

CHAPTER 7

SUMMARY

Summary

Anomalies in speech production may be found in the speech of the post-lingual deaf. Cochlear implantation partially restores the auditory feedback. The renewed perception of their own voice may improve the quality of the speech of cochlear implant users. In this thesis several aspects of speech production of twenty post-lingually deafened subjects are described before and after implantation with the Nucleus 22 cochlear implant. Speech recordings were made pre-implantation and three and twelve months post-implantation with the implant switched on and off. As the Nucleus 22 implant predominantly conveys segmental information essential for vowel identification, our first study was directed toward the effect on vowel production (Chapter 2). After implantation, with the implant switched on, we found, using LPC-analysis, an increase in the ranges of the first and second formant frequencies (F_1 and F_2) covered by the respective vowels. In addition, we found that both F_1 and F_2 changed toward their norm values. Furthermore, we found an increase of the clustering of the respective vowels, implying an improvement in the ability to make phonological contrasts between vowels.

In chapter 3 we studied whether the objective improvements found in chapter 2 resulted in an increase of vowel intelligibility. The group of post-lingually deafened subjects is a very heterogeneous one, therefore, we presented the speech materials from all twenty subjects to listeners in a noisy background to avoid near-perfect intelligibility scores for the better subjects. After implantation with the implant switched on we found an increase in vowel intelligibility scores for most subjects. These results were consistent with individual subjective observations of 'co-therapists' of cochlear implant users who reported that speech intelligibility improved in noisy surroundings. However, we found higher vowel identification scores at three months post-implantation with the implant switched on than at twelve months post-implantation with the implant switched on. This suggests that after an initial period of intense attention for their own speech production, a period may follow in which the perception of one's own speech is taken for granted resulting in less accurate vowel production. Switching off the implant resulted in lower scores at three months implantation. However, at twelve months post-implantation no significant differences were seen between the conditions with the implant switched on and off. The latter result suggests that at the beginning of the rehabilitation period implant users pay more attention to the auditory information provided by the implant, resulting in improved vowel production with the implant

switched on as compared to the implant switched-off condition. However, the differences between the mean vowel identification scores across all subjects in the five conditions were small.

Interestingly, we found that the increase in vowel intelligibility scores was significantly correlated with some of the objective measurements of the previous study, involving the formant measurements. The vowel intelligibility scores appear to be mainly determined by the position of the second formant frequencies.

In addition, we determined vowel intelligibility in quiet for seven poor quality speakers, who without noise, would give intelligibility scores below 100%. Post-implantation we found a significant increase in vowel intelligibility as compared to pre-implantation. However, the increase in mean vowel identification scores was small. Again, we noted significant correlations with the objective formant measurements. The strongest correlations were found between the intelligibility scores and both the frequency range of F_2 and the deviation of F_2 from the norm values.

The next topic dealt with the question which acoustic features of vowels produced by the post-lingual deaf are used by the listeners in a vowel identification task. We found that the listeners used both F_1 and F_2 information to identify the vowels. For the subgroup of poorly performing speakers in quiet, we noted that the listeners also used the duration of the vowels in the identification task.

Besides formant information the Nucleus 22 implant also conveys fundamental frequency information. Chapter 4 describes the effect of implantation on voice fundamental frequency (f_0). Post-implantation, we found that abnormally high f_0 values pre-implantation changed toward the norm values. In the literature, however, the results about the effect of the renewed auditory feedback on f_0 are quite varied. The present study shows that these differences may be due to the large interindividual differences between subjects. Also, we found that post-implantation the range over which f_0 varied, the f_0 sway, decreased for most subjects who had too large f_0-sways pre-implantation. Interestingly, this study suggests that f_0 is directly controlled by the auditory feedback from the implant.

Some authors report that the Nucleus implant also conveys information about nasality. The effect of cochlear implantation on nasality was studied in chapter 5. The results show that pre-implantation the nasalance value (Kay Elemetrics) of most post-lingually deafened subjects in our study fell already within the normal range.

We found no significant effect of implant use. Nonetheless, individual deviant nasality values may improve after implantation.

In chapter 6 a perceptual evaluation of speech production was carried out. Students of speech and language pathology judged speech fragments of our implant users on 21 questions, involving both segmental and suprasegmental aspects of speech production. Post-implantation, we found significant improvements in voicing aspects and vowel production as compared to pre-implantation. In addition, post-implantation higher ratings were found in the implant switched-on condition as compared to the switched-off condition, again suggesting a direct control through the implant. This study also showed large interindividual differences between the subjects and in addition, different effects of implantation on speech production for individual subjects. Furthermore, this study showed that subjects with a duration of profound hearing loss of less than 10 years had better speech quality than those with a profound hearing loss of more than 10 years. The differences between these groups remained post-implantation. These differences appeared to be larger than the relatively small effects of implantation.

Interestingly, we found significant relations between the subjective evaluation of speech production and the objective measurements of vowel formants, vowel intelligibility and f_0. We noted significant correlations between the segmental ratings and the frequency range of F_1 and F_2, the deviations of F_2 from the norm positions and the vowel intelligibility scores. In addition, we found significant correlations between the subjective ratings of voice fundamental frequency and the objective measurements of mean f_0.

In summary, after cochlear implantation significant improvements occur in speech produced by the post-lingually deafened, implying that the auditory information from the implant is used to improve their speech production. However, all studies show large interindividual differences between the subjects in both the pre-implantation values and the effects of cochlear implantation. Although, we did find statistically significant effects of cochlear implantation, the mean effects for the whole group of subjects are generally small.

Relation between speech perception and speech production

Post-implantation we found the strongest correlations between the consonant-vowel-consonant (CVC)-perception scores and the deviations of F_1 and F_2 from the norm frequencies and the frequency range of F_2 (Chapter 2), the identification-in-noise scores of the vowels produced by the implanted subjects (Chapter 3), the mean f_0 (Chapter 4) and loudness control (Chapter 6), respectively.

Relation of speech production and duration of deafness

Pre-implantation we found the strongest correlation between the duration of deafness and both the deviation of F_2 from the norm frequencies and the frequency range of F_2 (Chapter 2). Additionally, we found significant correlations with the questions concerning the general impression of speech production and questions concerning loudness control and articulatory aspects (Chapter 6). Post-implantation we noted significant correlations between duration of deafness and the CVC-perception scores, the deviation of F_2 from the norm frequencies, the F_2-range (Chapter 2), questions concerning the general impression of speech production and questions concerning both loudness control and articulatory aspects (Chapter 6). Interestingly, the correlation between the duration of deafness and the deviation of F_2 from the norm values, the rating of vowel quality and consonant substitution is weaker at twelve months post-implantation than pre-implantation. This implies that the difference in speech production between subjects with a longer duration of deafness and subjects with shorter durations of deafness decreases after implantation. However, the opposite is found for the variables: F_2-range, vowel intelligibility scores in noise and intonational aspects. These variables suggest that the largest improvements are found for the relatively better performers, who are found mostly in the short duration of deafness group. The results of chapter 6 showed that the differences in speech quality between groups of subjects classified according to duration of deafness remained after cochlear implantation.

Implications for rehabilitation and speech quality evaluation

The results of this thesis suggest that in most cases rehabilitation concerning f_0 and nasality did not require speech training; auditory training sufficed. However, in some subjects therapy directed at speech production itself may be helpful. In considering segmental aspects speech therapy might be useful for those poorly performing subjects showing too little progress when given auditory training alone. However, it should be realized that in some subjects an initial deterioration of speech production may occur as a result of the renewed auditory feedback. In these cases improvements may occur only after a longer period of implant use, suggesting that an initial decrease in quality of speech production should not discourage the implanted individual nor the therapist.

Concerning the evaluation of speech production the results of this thesis suggest that it will be sufficient to study the effect of cochlear implantation on f_0, F_1, F_2 and the ratings pertaining to voice quality.

Samenvatting

Bij post-linguaal dove volwassenen vinden wij vaak afwijkingen in de spraakproduktie. Met behulp van een cochleair implantaat kunnen doven opnieuw geluiden en dus ook hun eigen spraak waarnemen. De auditieve informatie die het cochleair implantaat biedt over de eigen spraak zou kunnen leiden tot een verbeterde kwaliteit van de spraakproduktie. In dit proefschrift worden verschillende aspecten van de spraakproduktie van twintig post-linguaal dove volwassenen voor en na implantatie met het Nucleus 22 cochleair implantaat beschreven. Bandopnamen zijn gemaakt voor implantatie en drie en twaalf maanden na implantatie met het implantaat aan- en uitgeschakeld. Omdat het Nucleus 22 implantaat hoofdzakelijk segmentele informatie geeft die van belang is voor klinkeridentificatie, hebben wij ons in het eerste onderzoek gericht op de invloed op de klinkerproduktie (Hoofdstuk 2). Na implantatie, met het implantaat aan, vonden wij met behulp van een LPC-analyse een toename in het bereik van de eerste en tweede formant frequenties (F_1 en F_2) van de desbetreffende klinkers. Daarnaast vonden wij dat de F_1 en F_2 waarden dichter bij de normwaarden kwamen te liggen. Bovendien zagen wij een toename in de clustering van de individuele klinkers. Dit suggereert dat er na implantatie sprake is van een groter fonologisch contrast tussen de klinkers.

In hoofdstuk 3 hebben we onderzocht in hoeverre de objectieve verbeteringen gevonden in hoofdstuk 2 resulteerden in een toename van de klinkerverstaanbaarheid. Omdat er grote variabiliteit is in de mate waarin het gehoorverlies de spraak van post-linguaal doven heeft beïnvloed, hebben wij om teveel 100% scores te voorkomen het spraakmateriaal van de implantaat-gebruikers in achtergrondruis aangeboden aan een panel van luisteraars. Na implantatie, met het implantaat aan, was er bij de meeste implantaatgebruikers sprake van een toename in de klinkerverstaanbaarheidscores. Deze resultaten zijn overeenkomstig de subjectieve bevindingen van 'co-therapeuten' van de implantaatgebruikers die opmerkten dat de spraakverstaanbaarheid toeneemt in een lawaaiige omgeving. We vonden echter drie maanden na implantatie met het implantaat aan hogere klinker-identificatiescores dan twaalf maanden na implantatie. Dit impliceert dat na een periode van intensieve aandacht voor de eigen spraak, een periode kan volgen waarin de perceptie van de eigen spraak als meer vanzelfsprekend wordt ervaren, met als gevolg minder nauwkeurige klinkerprodukties. Drie maanden na implantatie resulteerde het uitschakelen van het implantaat in lagere klinkerverstaanbaarheidscores. Twaalf maanden na implantatie vonden wij echter geen verschil tussen de implantaat aan- en uit-conditie. Dit resultaat suggereert ook dat de implantaatgebruikers in het begin van de revalidatie meer gericht zijn op de auditieve informatie van het implantaat, met als gevolg betere klinkerprodukties met het implantaat aan dan uit. De verschillen tussen de gemiddelde klinkerverstaanbaarheidscores in de vijf verschillende condities zijn echter klein.

Opmerkelijk was dat de toename in de klinkerverstaanbaarheidscores significant gecorreleerd was aan de formantmetingen van de vorige studie. De klinkerverstaanbaarheidscores bleken hoofdzakelijk bepaald te zijn door de tweede formant frequenties.

Daarnaast bepaalden we de klinkerverstaanbaarheid van zeven "zwakke" sprekers, die zonder ruis verstaanbaarheidscores zouden geven lager dan 100%. Na implantatie vonden we een significante toename in de klinkerverstaanbaarheidscores vergeleken met die voor implantatie. De gemiddelde toename was echter klein. Opnieuw zagen we significante correlaties met de objectieve formantmetingen. De sterkste correlaties werden gevonden tussen de klinkerverstaanbaarheidscores en zowel het frequentiebereik van de F_2 als de afstand van de F_2 tot de normwaarden.

Vervolgens werd nagegaan welke akoestische kenmerken van de klinkers geproduceerd door de post-linguaal dove volwassenen door de luisteraars gebruikt werden voor de klinkeridentificatie. De resultaten toonden aan dat de luisteraars zowel de F_1 als de F_2 informatie gebruikten om de klinkers te identificeren. Voor de zwakke sprekers zonder achtergrondruis, vonden we dat de luisteraars voor de identificatie ook gebruik maakten van de klinkerduur.

Naast formantinformatie geeft het Nucleus implantaat ook informatie over de toonhoogte. Hoofdstuk 4 beschrijft het effect van implantatie op de spreektoonhoogte (f_0). Na implantatie veranderden abnormaal hoge f_0 waarden in de richting van de normwaarden. In de literatuur vonden we wisselende resultaten met betrekking tot het effect van de herstelde auditieve feedback op f_0. De huidige studie toont aan dat deze verschillen het gevolg kunnen zijn van de grote individuele verschillen tussen de implantaatgebruikers. Daarnaast bleek dat na implantatie het bereik waarover de f_0 varieerde bij de meeste implantaatgebruikers, die een te groot f_0 bereik hadden, afnam.
Bovendien suggereren de resultaten van dit onderzoek dat de f_0 direct gecontroleerd wordt door de auditieve feedback van het implantaat.

Enkele onderzoekers in de literatuur geven aan dat het Nucleus implantaat ook informatie geeft over het kenmerk nasaliteit. Het effect van cochleaire implantatie op de nasaliteit is onderzocht in hoofdstuk 5. De resultaten geven aan dat de zogenaamde nasalanswaarden van de meeste post-linguaal dove volwassenen van onze studie binnen het normale bereik vallen. We zagen geen significant effect als gevolg van het gebruik van het implantaat. Niettemin, kunnen individueel afwijkende nasalanswaarden verbeteren na implantatie.

In hoofdstuk 6 worden de resultaten van een subjectieve analyse van de spraakproduktie beschreven. Studenten logopedie beoordeelden spraakfragmenten van de implantaatgebruikers op 21 items, betreffende zowel segmentele als suprasegmentele aspecten van de spraakproduktie. Na implantatie vonden we significante verbeteringen in stemaspecten en klinkerprodukties vergeleken met de situatie voor implantatie. Bovendien vonden we hogere scores in de implantaat aan-conditie dan in de implantaat uit-conditie. Dit suggereert opnieuw de directe controle via het implantaat. Deze studie laat ook grote interindividuele verschillen zien tussen de implantaatgebruikers. Verder geeft deze studie aan dat de effecten van implantatie tussen de implantaatgebruikers aanmerkelijk verschillen. Tenslotte toont deze studie dat implantaatgebruikers met een duur van doofheid korter dan tien jaar een betere spraakkwaliteit hebben dan die met een duur van doofheid langer dan tien jaar. Deze verschillen tussen de groepen bleven ook bestaan na implantatie. Blijkbaar is dit effect groter dan de relatief kleine implantaat-effecten.

Interessant is dat we significante correlaties vonden tussen de subjectieve evaluatie van de spraakproduktie en de objectieve metingen aan klinkerformanten, klinker-verstaanbaarheid en f_0. We vonden significante correlaties tussen de subjectieve beoordelingsscores en het frequentiebereik van de F_1 en F_2, de afwijking van F_2 tot de normwaarden en de klinkerverstaanbaarheid scores. Verder zagen we significante correlaties tussen de subjectieve beoordelingsscores en de objectieve metingen aan de gemiddelde f_0.

Samenvattend vonden we significante verbeteringen in spraak geproduceerd door post-linguaal dove volwassenen na cochleaire implantatie, aantonend dat zij de auditieve informatie van het implantaat gebruiken om hun spraakproduktie te verbeteren. Echter, alle onderzoeken laten grote interindividuele verschillen zien tussen de implantaatgebruikers in zowel de pre-implantatie waarden als in de effecten van cochleaire implantatie. Hoewel we significante effecten van cochleaire implantatie vonden, waren de gemiddelde effecten voor de gehele groep over het algemeen klein.

Relatie spraakperceptie en spraakproduktie

Na implantatie vonden we sterke correlaties tussen de consonant-vocaal-consonant (CVC)-perceptiescores enerzijds en de afwijking van F_1 en F_2 tot de normwaarden en het frequentiebereik van F_2 (Hoofdstuk 2), de klinkeridentificatiescores in ruis (Hoofdstuk 3), de gemiddelde f_0 (Hoofdstuk 4) en de controle over het volume van de stem (Hoofdstuk 6) anderzijds.

Relatie spraakproduktie en duur van de doofheid

Voor implantatie vonden we sterke correlaties tussen de duur van de doofheid en zowel de afwijking tussen de F_2 en de normwaarden en het frequentiebereik van F_2 (Hoofdstuk 2). Daarnaast vonden we significante correlaties met de items van de vragenlijst met betrekking tot de algemene indruk en volumecontrole en articulatorische aspecten (Hoofdstuk 6). Na implantatie zagen we significante correlaties met de CVC-perceptiescores, de afwijking van de F_2 tot de normwaarden, het F_2-bereik (Hoofdstuk 2), vragen met betrekking tot de algemene indruk en volumecontrole en articulatorische aspecten (Hoofdstuk 6). Opmerkelijk is dat de correlatie tussen de duur van doofheid en de afwijking van de F_2 tot de normwaarden, de beoordeling van de klinkerkwaliteit en consonant substitutie twaalf maanden na implantatie zwakker is dan voor implantatie. Dit wekt de indruk dat het verschil in spraakproduktie tussen sprekers met een langere duur van doofheid en een kortere duur van doofheid afneemt. Echter, het tegengestelde wordt gevonden voor de variabelen: F_2-bereik, klinkeridentificatiescores in ruis en intonatie. Deze resultaten suggereren dat de grootste vooruitgang wordt gezien bij de relatief betere sprekers. De resultaten in hoofdstuk 6 laten zien dat verschillen in spraakkwaliteit tussen de groepen implantaatgebruikers op basis van duur van doofheid ook na cochleaire implantatie blijven bestaan.

Implicaties voor de revalidatie en evaluatie van de spraakkwaliteit

De resultaten van dit proefschrift geven aan dat in de meeste gevallen de revalidatie met betrekking tot de spreektoonhoogte en nasaliteit zich kan beperken tot een auditieve training. Slechts voor een aantal implantaatgebruikers is expliciete logopedische therapie gericht op deze aspecten noodzakelijk. Wat betreft de articulatorische aspecten kan logopedie zinvol zijn voor die implantaatgebruikers die te weinig vooruitgang laten zien bij uitsluitend auditieve training. Hierbij moet men zich wel realiseren dat bij een aantal implantaatgebruikers er in eerste instantie sprake was van een achteruitgang in de spraakkwaliteit na implantatie. Bij deze groep zagen we een verbetering optreden na een langere periode van implantaatgebruik, wat suggereert dat een aanvankelijke achteruitgang in de spraakproduktie de implantaatgebruiker en logopedist niet moet ontmoedigen.

Wat betreft de evaluatie van de spraakproduktie suggereren de resultaten van dit proefschrift dat volstaan zou kunnen worden met het bepalen van het effect van cochleaire implantatie op de f_0, F_1, F_2 en het beoordelen van de stemkwaliteit.

Na implantatie vonden we [illegible] correlaties tussen de [illegible] en de afwijking van F_1 en F_2 [illegible] normwaarden en het frequentiebereik [illegible] (Hoofdstuk 2) [illegible] de controle over het volume van de stem [illegible] (Hoofdstuk 6) [illegible].

Relatie spraakproduktie en duur van de doofheid

Voor implantatie vonden we sterke correlaties tussen de duur van de doofheid en zowel de afwijking tussen de F_2 en de normwaarden en het frequentiebereik van F_0 (Hoofdstuk 2). Daarnaast vonden we significante correlaties met de items van de vragenlijst met betrekking tot de algemene indruk en volumecontrole en articulatorische aspecten (Hoofdstuk 6). Na implantatie zagen we significante correlaties met de CVC-percentagescores, de afwijking van de F_2 tot de normwaarden, het F_0-bereik (Hoofdstuk 2), [illegible] met betrekking tot de algemene indruk en volumecontrole en articulatorische aspecten (Hoofdstuk 6). Opmerkelijk is dat de correlatie tussen de duur van doofheid en de afwijking van de F_2 tot de normwaarden, de beoordeling van de klinkerkwaliteit en [illegible] na implantatie sterker is dan voor implantatie. Dit [illegible] dat het verschil in spraakproduktie tussen sprekers met een langere duur van doofheid en een kortere duur van doofheid [illegible] wordt gevonden voor de variabelen F_0-bereik, [illegible]. Deze resultaten suggereren dat de grootste verbetering wordt gezien bij de relatief korter dove sprekers. De resultaten in hoofdstuk 6 laten zien dat verschillen in spraakkwaliteit tussen de groepen implantatiegebruikers op basis van duur van doofheid ook na probleemloze implantatie blijven bestaan.

Implicaties voor de revalidatie en evaluatie van de spraakproduktie

De resultaten van dit proefschrift tonen aan dat in de meeste gevallen de revalidatie met betrekking tot de spraakproduktie [illegible] tot een auditieve training. Slechts voor een aantal implantaatgebruikers is [illegible] logopedische therapie gericht op deze aspecten noodzakelijk. [illegible]

Appendix I

Individual cases:

Subject 1:
In this subject we found at twelve months post-implantation a change in the first (F_1) and second (F_2) formant frequencies toward the norm values. In addition, we found that the variability of the F_2 decreased. Switching off the implant at twelve months post-implantation resulted in an increase in F_1-variability. The largest improvement in vowel intelligibility measured in a background of noise was seen at three months post-implantation with the implant switched on. Switching off the implant resulted in lower scores.
The f_0 measurements showed no significant change in the mean f_0 after implantation, but his intonation improved after implantation with the implant switched on. This in agreement with the results of the subjective analysis in which we also noted a significant improvement at twelve months post-implantation in his intonation. In addition, the subjective ratings showed significant differences between the conditions three months post-implantation with the implant switched on and off resulting in a deterioration of speech production with the implant switched off for the following questions: pleasantness of speech production (1), voice quality (6), loudness control (11), speech rate (12), number of pauses in speech production (14) and nasality (16). At twelve months post-implantation we found some on/off effects resulting in a deterioration for the questions in the implant switched-off condition: voice fundamental frequency (8), number of pauses in speech production (14) and consonant omissions (19).
Conclusion: Although, we found only little improvements in speech production post-implantation as compared to pre-implantation the better performance in the implant-on as compared to the implant-off conditions suggests that this subject is using the information from the implant to monitor his speech production.

Subject 2:
In this subject we found that the F_1-distance to the norm values increased twelve months post-implantation. The F_1-variability, however, decreased twelve months post-implantation with the implant on and off as compared to pre-implantation.

Twelve months post-implantation we also found an increase in the intelligibility-in-noise scores of the vowels as compared to pre-implantation. No effects of implantation were seen on the mean f_0. The f_0-sway, the range over which f_0 varied, showed a substantial decrease twelve months after implantation, which corresponded to subjectively improved intonation. Interestingly, switching off the implant at twelve months post-implantation resulted again in an increase of the f_0-sway. Twelve months post-implantation we found an increase of the nasalance value of the non-nasal sentences.
The subjective ratings for this subject showed an improvement at three and twelve months post-implantation with the implant switched on and off as compared to the pre-implantation condition for the questions: pleasantness of speech production (1), intelligibility (2), voice quality (6), voice control (7), voice fundamental frequency (8) and loudness control (11). The higher ratings of intelligibility and voice control are in accordance with the objective measurements. At three months post-implantation with the implant switched on we noted lower ratings for the variable speech rate (12) as compared to the implant switched-on condition and pre-implantation.
Conclusion: This subject is using the information from the implant to improve his speech production.

Subject 3:
The objective measurements of vowel production showed only minor effects. We found no significant effect on the F_1 and F_2-range. We found an increase in F_1- and F_2-variability at twelve months post-implantation. We did however, find an increase in the vowel intelligibility scores in noise at twelve months post-implantation. We found a small lowering of mean f_0 after implantation, which resulted in a closer to normal mean f_0. The f_0-sway showed no apparent differences after implantation.
The subjective ratings of this subject showed that at three months post-implantation with the implant switched on we found an improvement in pleasantness of speech production (1), intelligibility (2) and nasality (16). However, at twelve months post-implantation we only found some improvements in the questions: stress pattern (10), speech rate (12), number of pauses in speech production (14) and consonant distortion (20). Switching the implant off at twelve months post-implantation resulted in decreased ratings of pleasantness of speech (1), speech rate (12) and nasality (16).
Conclusion: In this subject we found at twelve months post-implantation effects on

suprasegmental aspects of speech production and some minor effects on consonant and vowel production.

Subject 4:

The objective measurements of vowel production showed at three and twelve months post-implantation a non-significant increase in the F_1 and F_2 range and a decrease of the distances to the norm values for F_2. The vowel intelligibility in noise increased after implantation. The largest improvement was found three months post-implantation with the implant switched on. Similar results were found for the vowel intelligibility scores in quiet. Furthermore, we found a small lowering of f_0 after implantation which resulted in a value closer to the normal value. The f_0-sway decreased at three months post-implantation which resulted in a more monotonous intonation. At twelve months post-implantation his intonation covered a wider range. Post-implantation we found an improvement of the nasalance scores when reading the non-nasal sentences.

The subjective ratings also showed the largest improvements at three months post-implantation with the implant switched on. We noted improved ratings for intelligibility (2), articulation (4), voice fundamental frequency (8), place of pauses (15), vowel production (17), consonant production (19-20) and syllable deletion (21). At twelve months post-implantation we found improvements as compared to pre-implantation in intelligibility (2), voice fundamental frequency (8), place of pauses (15) and nasality (16). Furthermore, we found significant higher ratings for intelligibility with the implant switched on as compared to the implant-off condition. However, no significant improvements in vowel and consonant production were noted at twelve months post-implantation, which is in agreement with the vowel intelligibility measurements. The objective improvements in mean f_0 are consistent with the subjective ratings. The objective found changes in f_0-sway, are not found in the subjective measurements.

Conclusion: Although significant improvements were also found at twelve months post-implantation, this subject showed the largest improvements at three months post-implantation.

Subject 5:

The vowel formant measurements showed no significant effect of cochlear implantation on the F_1 and F_2 range. We found a decrease of F_1 and F_2 variability after implantation. The vowel identification task showed a large improvement in vowel identification scores at twelve months post-implantation. Three months post-implantation the vowel identification scores were lower than pre-implantation. No significant effects on f_0 were found after implantation.

In examining the mean results of the subjective experiment we found an obvious improvement at three and twelve months post-implantation. Significant improvements were found for the questions: pleasantness of speech production (1), intelligibility (2), prosody (3) and articulation (4), voice control (7), intonation (9), stress pattern (10), speech rate (12) and rhythm (13) and segmental aspects (16-21). In addition, we found significant differences between the ratings with the implant switched-on and off at three months post-implantation. With the implant switched on higher ratings were given for both suprasegmental and segmental aspects of speech production. Twelve months post-implantation we found no significant differences between the implant switched-on and off condition. The subjective improvement in intonation had no counterpart in the objective measurements of f_0. The subjective improvements in vowel production, however, are also seen in the objective measurements.

Conclusion: This subject showed large improvements in speech production after implantation, considering both suprasegmental and segmental aspects of speech production. In addition, significant effects of switching the implant on and off were found at three months post-implantation.

Subject 6:

Twelve months post-implantation we found a significant increase of the F_1-range. Also, the F_1-distance decreased. The F_2-distance to the norm values, however, increased. The vowel intelligibility scores in noise increased after implantation, which is not consistent with the results in quiet showing no improvement after implantation. The f_0-measurements showed a lowering of f_0. The f_0 values, however, remained within the normal range. Also, the f_0-sway remained within the normal range, except for the condition twelve months post-implantation with the implant switched off, showing a too large f_0-sway.

The subjective measurements showed significant deteriorations at twelve months post-implantation with the implant switched on for the questions: pleasantness of speech production (1), intelligibility (2), articulation (3), voice fundamental frequency (8), intonation pattern (9), vowel production (17), consonant production

(18,20) and deletion of syllables (21). No significant on/off effects of switching the implant on and off were found.
Conclusion: For this subject the implant had mainly negative effects on speech production. This subject had only limited benefit from the implant.

Subject 7:
Improvements in vowel production were mainly found at twelve months post-implantation with the implant switched on. In vowel production we noted a significant increase of the F_1-range. In addition, we found a change of both formant frequencies toward the norm values. Three months post-implantation we found a decrease in F_2-variability. These results are in agreement with the increase in vowel identification scores in noise at twelve months post-implantation but not with those at three months post-implantation. For the f_0-measurements we found a lowering of f_0 after implantation. The f_0 value remained within the normal range. Pre-implantation, speech was monotonous. After implantation we found no improvement.
Also, in the subjective evaluation large improvements were found at twelve months post-implantation. With the implant switched on we noted higher ratings as compared to pre-implantation for the questions: pleasantness of speech production (1), intelligibility (2), prosody (3), voice control (7), stress pattern (10), number and placing of pauses (14,15), vowel production (17) and consonant distortion (20). At three months post-implantation we noted higher ratings with the implant switched off than with the implant switched on for the questions: pleasantness of speech production (1), intelligibility (2), stress pattern (10) and vowel production (17).
Conclusion: This subject showed largest improvements at twelve months post-implantation. At three months post-implantation higher ratings were mostly found for the implant switched-off condition. Possibly, this subject needed more time to use the auditory feedback of the implant to improve speech production.

Subject 8:
The vowel formant measurements showed a decrease of the F_1 range at three months post-implantation, but the range was larger at twelve months post-implantation than at pre-implantation. This also held for the F_1-distance. The F_2-distance decreased twelve months post-implantation. Also, the F_1-variability

decreased after implantation. The F_2-variability was increased at three months post-implantation. Thus, the largest improvements in vowel production are noted twelve months after implantation. These results are not consistent with the vowel intelligibility scores in noise showing no improvement after implantation. The results are however, similar to the results in quiet showing the largest increase in vowel identification scores at twelve months post-implantation. In addition, we found a lowering of f_0 into the direction of the normal range. Pre-implantation the f_0-sway was too large. The f_0-sway twelve months after implantation fell within the normal range. The nasality measurements showed no significant effects of implantation.
Three and twelve months post-implantation the subjective measurements showed improvements in mostly segmental aspects of speech production: intelligibility (2) and articulation (4), vowel production (17), and consonant production (18-20). However, also some improvements were found in the number of pauses in speech production (14) and speech rate (12). The objectively measured improvements in f_0 were not seen in this study. This may be related to the fact that f_0 was still too high after implantation. At three months post-implantation we found significant short-term effects of switching the implant on and off for: intelligibility (2), voice control (7), voice fundamental frequency (8), number of pauses in speech production (14) and consonant distortion (20). With the implant switched on higher ratings were found. At twelve months post-implantation we found no significant differences between the conditions on and off.
Conclusion: This subject uses the information from the implant favourably to improve intelligibility of speech production.

Subject 9:
Post-implantation the objective measurements of vowel production showed an increase in the range of F_1 and F_2. At three months post-implantation we also found a decrease of the F_1-variability. At twelve months post-implantation we found a decrease of F_2 to the norm values. Both three and twelve months post-implantation we found an increase of the vowel intelligibility scores in noise. In addition, we noted a lowering of f_0 after implantation resulting in f_0 values within the normal range. Also, the f_0-sway decreased to values within the normal range. No significant effect on nasality was found.
In the subjective evaluation we found mainly changes at three months post-implantation. We found significant improvements for the questions: pleasantness of

speech production (1), prosody (3), voicing (5), voice quality (6), voice control (7), voice fundamental frequency (8), loudness control (11) and rhythm (13). Significant on/off effects were found for the questions: voice quality (6) and voice control (7), loudness control (11) and consonant distortion (20). Higher ratings were given for the switched-on condition.

However, at twelve months post-implantation we found a significant improvement as compared to pre-implantation for the questions: pleasantness of speech production (1) and voice fundamental frequency (8), which is consistent with the objective measurements of f_0.

Conclusion: Most improvements in speech production were found at three months post-implantation.

Subject 10:

The vowel formant measurements indicated a decrease of the F_1-distance to the norm frequencies at three and twelve months post-implantation. The F_2-distance to the norm frequency, however, increased at twelve months post-implantation with the implant on. In addition, we noted a decrease of the F_2-variability at three months post-implantation. In examining the vowel intelligibility scores in noise we found an increase at both three and twelve months post-implantation. Also, we found that the f_0, although within the normal range in all conditions, was higher in the implant switched-on condition. This resulted in values closer to the mean for female speakers. The f_0-sway was larger in the implant switched-off condition and pre-implantation than in the implant switched-on condition, resulting in values just outside the normal range. No effect on nasality was found.

Although some subjective improvements in speech production were already found at three months post-implantation, the largest improvements were found at twelve months post-implantation. We noted significantly higher ratings for the questions: pleasantness of speech production (1), prosody (3), articulation (4), voice fundamental frequency (8), intonation pattern (9), stress pattern (10), loudness control (11), speech rate (12) and nasality (16). Switching off the implant at twelve months post-implantation resulted in a more deviant voice fundamental frequency (8). Thus, the objectively found improvements in vowel production and f_0 are also seen in the subjective ratings from the students. The improvement in nasality, however, was not seen in the objective measurements.

Conclusion: This subject uses the auditory feedback from the implant to improve suprasegmental aspects of speech production and vowel production.

Subject 11:

We found little changes in the formant measures post-implantation. The vowel intelligibility scores in noise, however, display a large improvement at three months post-implantation and a decrease again at twelve months post-implantation with the implant switched on. In contrast, the vowel intelligibility scores in quiet showed no improvement after implantation, consistent with the formant measures. The mean f_0 did not change after implantation. The f_0-sway, which fell outside the normal range pre-implantation increased to a normal value post-implantation. In examining nasality we noted an improvement in nasality three months post-implantation. At twelve months post-implantation we found a relapse for this subject.

Also in the subjective evaluation we noted little changes in speech production. Only, at three months post-implantation an improvement in voice production was seen. However, at twelve months post-implantation the ratings were again more comparable to the pre-implantation ratings.

Conclusion: This subject showed very little effect of cochlear implantation on speech production.

Subject 12:

The formant measurements showed an increase of the F_1-range after implantation both in the implant on and off conditions. Also, a decrease of the F_1 and F_2 distances to the norm values was seen in all post-implant conditions. However, we found an increase in F_1 variability at twelve months post-implantation with the implant switched on and off. The increase in F_1 variability was larger in the implant-off condition. The F_2-variability increased at three months post-implantation with the implant switched off. The vowel intelligibility scores in noise showed the largest improvement at three months post-implantation with the implant switched on. Switching off the implant resulted in lower scores. The mean f_0 and the f_0-sway were within the normal range both pre- and post-implantation. However, larger f_0-sways were found post-implantation. No effect on nasality was found.

The subjective ratings showed significant deteriorations in speech production when the implant was switched off both at three months and twelve months post-implantation. No significant differences were found between the pre-implantation ratings and the implant switched-on conditions. Three months post-implantation with the implant switched off we found lower ratings as compared to pre-implantation for the questions: pleasantness of speech production (1), intelligibility (2), prosody (3), articulation (4), voicing (5), nasality (16) and vowel production (17). At twelve months post-implantation with the implant switched off lower rating were found for the questions: pleasantness of speech production (1), intelligibility (2), voice quality (6), voice fundamental frequency (8) and vowel production (17). Conclusion: Although we found improvements in vowel intelligibility we found no improvements in the ratings of speech production as compared to the pre-implantation ratings. However, we found obvious differences between the implant switched on and off conditions resulting in lower ratings with the implant switched off. Similar results were also seen in an increase in F_1 and F_2 variability of vowel production when the implant was switched off. An explanation for these results may be that this subject was still using her hearing aid at the time of the pre-implantation measurements. With the limited information from this hearing aid she was still able to control her speech production. Two months after implantation she stopped using the hearing aid. Consequently, the recordings post-implantation with the implant switched off are made without any auditory feedback, resulting in lower ratings. The higher ratings with the implant switched on suggest the favourable use of auditory information provided by the implant to control her speech production.

Subject 13:

We found only minor changes in the formant measures. Three months post-implantation with the implant switched off we found an increase in F_1-range. At twelve months post-implantation we found a change of F_2 into the direction of the norm values. The F_1-variability increased at three months post-implantation and the F_2-variability increased at twelve months post-implantation with the implant switched off. The vowel intelligibility scores both in noise and in quiet showed no change after implantation. The mean f_0, however, changed into the direction of the normal values at twelve months post-implantation with the implant switched on. The f_0-sway remained within the normal range. No effect on nasality was seen. These objective results are consistent with the results from the subjective experiment showing minor positive changes in speech production at twelve months post-implantation. With the implant switched on we found an increase in the ratings for the questions: pleasantness of speech production (1), voice quality (6) and voice

fundamental frequency (8). However, we found a decrease in the ratings for the questions: intonation (9), stress pattern (10) and loudness control (11).
Switching the implant off at twelve months implantation resulted in a decrease in intelligibility (2) and less control of loudness (11).
Conclusion: Only few improvements in speech production were found in this subject. This subject had only minor benefit from the implant.

Subject 14:
The formant measurements showed a decrease of the F_1-distance to the norm values at three and twelve months post-implantation. The F_2-variability decreased post-implantation. The vowel intelligibility score increased at three months post-implantation, but decreased twelve months post-implantation to lower scores than at pre-implantation. The mean f_0 lowered post-implantation, but remained within the normal range. The f_0-sway decreased post-implantation. This meant an improvement in intonation. Switching off the implant resulted again in an increase of the f_0-sway. In addition, we found an improvement in nasality for this subject with the non-nasal sentences.
Three months post-implantation with the implant switched on the subjective ratings showed significant improvements in voice production, prosodic aspects of speech production and nasality. Switching off the implant resulted in lower ratings of the general aspects of speech production, voice production and nasality. However, no obvious differences were found for the prosodic aspects of speech production. However, at twelve months post-implantation we found a decrease in the ratings of the general aspects of speech production and consonant production (18,20). This is similar to the decrease in the vowel intelligibility scores at twelve months post-implantation. At this time, only improvements as compared to pre-implantation were found for prosodic aspects of speech production and nasality. Moreover, switching off the implant resulted in better results.
Conclusion: At three months post-implantation with the implant switched on significant improvements in speech production were found. However, twelve months post-implantation we found a deterioration of mostly segmental aspects of speech production.

Subject 15:
In this subject we found obvious improvements in vowel production. Both the F_1

and F_2 range increased and the F_1 and F_2 distances to the norm frequencies decreased post-implantation. In addition, we noted a decrease in the F_2-variability at twelve months post-implantation. However, the vowel intelligibility scores in noise showed a relatively small improvement at three and twelve months post-implantation. Post-implantation we found a lowering of the mean f_0 resulting in a value within the normal range. Switching off the implant resulted again in higher f_0 values closer to the pre-implantation value. The f_0-sway decreased at three months post-implantation resulting in monotonous intonation, while the pre-implantation sway was within the normal range. At twelve months post-implantation the f_0-sway value fell within the normal range again. No effects on nasality were found.
The subjective ratings show significant improvements at three and twelve months post-implantation with the implant switched on. Improvements were found for the general questions, voice production, voice fundamental frequency, prosodic aspects, segmental aspects (20) and nasality. Both at three months and at twelve months post-implantation significant differences were found between the conditions implant switched on and off, showing higher ratings with the implant switched on. Only at three months post-implantation the vowel production rating showed an improvement as compared to pre-implantation. This is consistent with the vowel intelligibility in noise score in which we also found that twelve months post-implantation the score decreased into the direction of the pre-implantation score. Also, the mean f_0-measurements are consistent with the rating on the voice fundamental frequency. The improvement in nasality however, was not found objectively.
Conclusion: This subject uses the auditory information from the implant to control speech production. Switching off the implant for only half an hour directly resulted in deterioration of speech production: values became more similar to the pre-implantation values.

Subject 16:

For this subject the vowel formant measurements showed the largest improvement at twelve months post-implantation with the implant switched on. The F_1 range increased, the F_1 and F_2 distances to the norm frequencies decreased and also the F_2-variability decreased. At three months post-implantation with the implant switched off and twelve months post-implantation we found a decrease of the F_1-variability. The vowel intelligibility scores in noise improved only at twelve months

post-implantation. The mean f_0 and the f_0-sway were within the normal range in all conditions, except for the mean f_0 at twelve months post-implantation with the implant switched off, where we found that the mean f_0 was too high. No effect on nasality was found.
Post-implantation in the subjective evaluation we only found a few changes. Twelve months post-implantation with the implant switched on the listeners judged speech production as less pleasant (1) than pre-implantation. Also, they judged speech production as more deviant on the questions: speech rate (12), number and places of pauses (14,15) and nasality (16).
Conclusion: In this subject cochlear implantation resulted in an objective improvement in vowel production at twelve months post-implantation. The subjective ratings showed some negative changes at twelve months post-implantation with the implant switched on.

Subject 17:
The vowel formant measurements showed a decrease of the F_1-distance to the norm values at three months post-implantation. In addition, the F_2-variability increased post-implantation. The vowel intelligibility scores in noise showed a large improvement at three months post-implantation. We found no effect on the mean f_0. The f_0-sway fell within the normal range pre-implantation at three and twelve months post-implantation with the implant switched on. Switching the implant off at twelve months post-implantation, however, resulted in more monotonous intonation. The nasalance value of the non-nasal sentences improved post-implantation.
The subjective ratings showed large improvements at three and twelve months post-implantation with the implant switched on as compared to pre-implantation. Again, switching off the implant resulted in significant deteriorations in speech production. Although, large improvements were already found at three months post-implantation, the largest improvements were seen at twelve months post-implantation. Higher ratings as compared to pre-implantation were found for mostly suprasegmental aspects of speech production (questions: 1,2,3,5,6,7,9,10,11,16 and 20).
Conclusion: This subject uses the auditory information from the implant to improve speech production. Switching off the implant resulted in a deterioration of speech production.

Subject 18:

Only few effects on vowel production were found in the objective measurements. Three months post-implantation with the implant switched on and off we found an increase of the F_1 and F_2-variability as compared to pre-implantation. The vowel intelligibility scores in noise only showed a deterioration at three months post-implantation with the implant switched off. We found no effect on mean f_0, which was already within the normal range pre-implantation. The f_0-sway fell just outside the normal range pre-implantation, but increased to the normal values post-implantation.

The subjective ratings showed at three months post-implantation, with the implant switched on, an improvement in voice control (7) as compared to pre-implantation. However, we noted lower ratings for consonant production and rhythm (13) as compared to pre-implantation. Higher scores for intelligibility (2) and consonant production were found for the implant-off condition as compared to the implant switched-on condition. Nonetheless, at twelve months post-implantation significant improvements in both suprasegmental (voice aspects and loudness control) and segmental (vowels and consonants) aspects were found. At twelve months post-implantation we noticed no significant differences between the conditions implant switched on and off.

Conclusion: After twelve months of implant use this subject can employ the information from the implant to improve speech production.

Subject 19:

We only found small improvements in the formant measurements. Twelve months post-implantation we noted a decrease of the F_1-distance to the norm values. The vowel intelligibility scores in noise showed a decrease at three months post-implantation with the implant switched on and an increase at twelve months post-implantation with the implant switched off. The vowel intelligibility scores in quiet increased twelve months post-implantation. The mean f_0 decreased post-implantation with the implant switched on to values within the normal range. Also, we found that the f_0-sway was very large before implantation, fell within the normal range at three months post-implantation and fell again outside the normal range at twelve months post-implantation with the implant switched on. Interestingly we found an even larger f_0-sway at twelve months post-implantation with the implant switched off. No effect on nasality was found.

The subjective ratings indicated significant improvements in speech production at both three months and twelve months post-implantation. However, changes in speech production were only seen at the suprasegmental level: pleasantness of speech (1), voicing (5), voice control (7), voice fundamental frequency and loudness control (11). In addition, at twelve months post-implantation large differences were found between the conditions implant switched on and off. Significant higher ratings were found for the implant-on condition as compared to the implant-off condition on the questions involving voice production (5-7), voice fundamental frequency (8), intonation (9), stress pattern (10) and loudness control (11).

Conclusion: This subject uses the auditory information from the implant mainly to control suprasegmental aspects of speech production. This may be related to her relatively low phoneme perception scores with the implant.

Subject 20:

The vowel formant measurements indicated an increase of the F_1-range twelve months post-implantation with the implant switched off. The F_1-distance to the norm values decreased twelve months post-implantation. Also, we found an improvement in the F_1 and F_2-variability post-implantation. The vowel intelligibility scores in noise improved three months post-implantation, but not at twelve months post-implantation. The vowel intelligibility scores in quiet showed the largest improvement at twelve months post-implantation, which is in agreement with the increase of the subjective rating of vowel production at twelve months post-implantation. The mean f_0 was within the normal range in all conditions. However, with the implant switched off f_0 was higher than with the implant switched on. The f_0-sway decreased twelve months after implantation resulting in more monotonous speech. We found an improvement in nasality three months after implantation. However, twelve months post-implantation the nasalance value changed into the direction of the pre-implantation value.

The subjective ratings showed at twelve months post-implantation with the implant on an obvious improvement in vowel production (17). However, voice quality (6) was judged negatively as compared to pre-implantation.

Conclusion: Speech production of this subject is only mildly affected by the auditory information from the implant.

List of abbreviations and acronyms

ANOVA	Analysis of Variance
CDT	Connected Discourse Tracking
CIS	Continuous Interleaved Sampling
CVC	Syllabe type: Consonsant-Vowel-Consonant
f_0	Fundamental frequency
F_1, F_2	First formant, Second formant
Kruskal	a specific multidimensional scaling technique
LPC	Linear Predictive coding
Mpeak	a specific processor strategy
MSP	Mini Speech Processor
sd	Standard deviation
S/N ratio	Signal-to-noise level
SPL	Sound pressure level
Tukey's HSD	Tukey's Honestly Significant Difference test
V	Vowel
WSP	Wearable Speech Processor

Curriculum Vitae

De schrijfster van dit proefschrift werd op 29 september 1966 te Hilversum geboren. Na het behalen van het diploma Atheneum aan Het Nieuwe Lyceum te Hilversum in 1984, studeerde zij van 1984 tot 1988 Logopedie aan de Akademie voor Logopedie in Groningen. In september 1988 begon zij met de studie Spraak- en Taalpathologie in Nijmegen. Haar doctoraal-diploma behaalde zij in augustus 1991. In september 1991 werd zij aangesteld als hoortherapeute van het Cochleair Implant Team in het Academisch Ziekenhuis Utrecht. In april 1991 is zij begonnen met wetenschappelijk onderzoek (onder leiding van Prof.dr. G.F. Smoorenburg, Dr.Ir. A.J. Bosman en Dr. A.F. van Olphen), dat heeft geresulteerd in dit proefschrift. Daarnaast is zij werkzaam als Spraak-en Taalpathologe op het Chr. instituut voor Doven Effatha te Voorburg.