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Speech Production by Users of Cochlear Implants:A Review[1]

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1. Introduction

There are several reasons why the study of speech production by cochlear implant users is important. First, it is a subject of clinical interest, particularly in the case of prelingually deaf children. This is because even though cochlear implants are primarily aids to speech perception, they are also an important aid in the development of speech production and oral language by children with congenital or prelingual, profound hearing impairment. In this chapter we review some of the extensive literature addressing changes in speech production as a function of cochlear implant use, in both adults and children. In the case of postlingually deafened adults, these changes are substantially more subtle than those observed in prelingually deaf children. However, they are of great theoretical interest because they shed light on the intricate relationship between speech perception and speech production in speakers with a mature language system (Tobey, 1993). Thus, the study of speech production by cochlear implant users represents an interesting new paradigm to explore the role of hearing in adult speech production.

We will discuss separately the study of pediatric and adult speakers. Both sections include longitudinal studies as well as "on-off" studies, that is, examination of the effect of turning off the speaker's speech processor, thereby depriving him/her of auditory input. In the section dealing with children, we will discuss their ability to speak intelligibly, the phonological properties of their speech and the study of acoustic and physiological characteristics of their speech. Postlingually deafened adults typically have high intelligibility and an intact phonological system, so in the second section we will only discuss acoustic and physiological studies.

2. Speech Production by Children Who Use Cochlear Implants

Throughout the 1980s, single-channel cochlear implants were the norm for use by both adults and children, but their use has become exceedingly rare since the advent of multichannel cochlear implants. We will primarily discuss the study of children with multichannel implants, but we will also cover some of the most important studies dealing with children who used single-channel cochlear implants (i.e., Kirk and Hill-Brown, 1985). Clinical trials in children of the Nucleus 22-channel cochlear implant were initiated in 1986, and in 1990, this device received U.S. Food and Drug Administration approval for use in children. The bulk of research on benefits of these devices for speech production and language development in children began during the clinical trials and have continued up to the present time.

2.1. Intelligibility

Insofar as cochlear implants may aid in the development of speech production skills in profoundly deaf children, of paramount importance is the development of overall speech intelligibility, that is, the ability simply to be understood. A number of studies, dating only to the early 1990s, have addressed the question of speech intelligibility of children who use cochlear implants, either in the context of other speech production measures or as the primary object of inquiry.

Two types of measures of speech intelligibility are in general use: (1) rating scales and (2) write-down procedures (Samar & Metz, 1988). With rating scales, listeners make explicit judgments about a talker's overall speech intelligibility by assigning numerical values to speech samples (e.g., the NTID rating scale: Subtelny, 1977). In write-down procedures, listeners "write down what they thought each child said" (Monsen, 1981). Metz, Schiavetti, and Sitler (1980) point out that write-down procedures have higher face validity than rating tasks, because listeners must actually comprehend what is being said. Additionally, these procedures are relatively insensitive to vocal qualities of speech, which may contaminate responses on a rating scale, but need not degrade message intelligibility (Samar & Metz, 1988). On the other hand, write-down procedures can be time consuming and labor intensive, which makes them more expensive (although see Samar & Metz, 1988), whereas rating tasks are considered to be "quick and easy" (Metz et al., 1980). Rating scales, especially equal-interval scales, are generally administered with experienced listeners (e.g., audiologists, speech-language pathologists) as judges, whereas write-down protocols can be administered with either experienced or inexperienced listeners. For example, the SPINE (Monsen, Moog, & Geers, 1988) is a write-down procedure in which the examiner is an experienced listener; this procedure has been used, for instance, in Geers and Moog (1991) with pediatric cochlear implant users.

Tobey, Angelette et al. (1991) reported results from five speech production protocols collected as part of the FDA's clinical trials for the Nucleus multichannel cochlear implant. Among these five protocols was the assessment of speech intelligibility. In this protocol, 27 children (14 with congenital etiologies of deafness and 13 with noncongenital etiologies) read 36 sentences developed by McGarr (1983). This set includes sentences of 3, 5, and 7 syllables in length and is divided equally between sentences with "high context" (e.g., "May I have a *piece* of cake?") and "low context" (e.g., "If it's *cool* I cannot go"). As indicated by the italics, each of the sentences contains a key word, for which the rest of the sentence provides either high or low context. Judges (three graduate students in speech-language pathology) listened to recordings of the children reading the sentences and wrote these down. Scoring was based on the total number of key words correctly identified. Results indicated that 62.9% of the children improved speech intelligibility after receiving a cochlear implant (measured at the one-year postimplant test session). Speech intelligibility was significantly higher after implantation ($M = 33.5$, $SD = 32.4$) than before ($M = 18.1$, $SD = 28.1$) ($t = 3.73$, $df = 26$, $p < .01$). Findings from the study just described were updated in Tobey and Hasenstab (1991). For the 24 users of Nucleus multichannel cochlear implants reported there, judges identified key words in the 36 McGarr sentences, just as in Tobey, Angelette et al. (1991). Speech intelligibility was assessed preimplant and at 6 or 12 months postimplant. Results showed significantly higher scores at the postimplant interval than at the preimplant interval ($t = -1.04$, $df = 18$, $p < .01$).

Osberger, Maso, and Sam (1993) introduced a number of innovations to research on the speech intelligibility of children using cochlear implants, examining intelligibility as a function of assistive device (cochlear implant or tactile aid) and age at device fitting. Additionally, Osberger et al. employed a write-down procedure similar to that used by Tobey, Angelette et al. (1991) and Tobey and Hasenstab (1991) but using naive listeners rather than trained ones (e.g., speech-language pathologists) as judges. Finally, children who used hearing aids served as controls. They were classified into three groups, according to their residual hearing. "Gold" hearing aid users had unaided pure-tone average thresholds (at 0.5, 1 and 2 kHz) between 90 and 100 dB HL, and "Silver" hearing aid users had thresholds between 100 and 110 dB HL. Comparisons were made of the speech intelligibility of 31 children who used the 3M/House single-channel implant ($n = 12$), the Nucleus multichannel implant ($n = 15$), or the Tactaid II+ two-channel vibrotactile aid ($n = 4$). Among the experimental subjects, 23 were determined to have early onset of deafness (before age 4) and 8 as having late onset (after age 4). Of the control subjects, 12 were classified as having early onset of deafness and 2 as late onset. All subjects produced 10 sentences each time they were tested; sentences were from Monsen (1983) or resembled these sentences in syntax and phonetics. These sentences were recorded, digitized, and randomized for playback to panels of judges who had no prior experience with the speech of hearing-impaired talkers; judges were instructed to write down the utterances they heard during playback. Intelligibility was measured as the percentage of words correctly transcribed, averaged across judges. Speech intelligibility baselines were established for experimental subjects from recordings taken prior to receiving devices, with subsequent measures collected at six-month intervals. Results showed that children with early onset of deafness who had received cochlear implants before age 10 demonstrated the highest scores among experimental groups (*M* = 25%), whereas children who did not receive cochlear implants until after age 10 had the lowest scores (*M* = 9%). On average, the postdevice speech intelligibility of children with early-onset deafness was similar to that of Silver hearing aid users. The speech intelligibility of children with late-onset deafness exhibited marked deterioration after onset but also showed marked improvement after fitting with a single- or multichannel cochlear implant.

Osberger, Robbins, Todd, Riley, & Miyamoto (1994) hypothesized that the improvements in speech intelligibility found in Osberger et al. (1993) might continue with increased device use, and thus examined the speech intelligibility of children who had used cochlear implants for up to five years. Additionally, the speech intelligibility of pediatric users of cochlear implants was compared to that of three groups of profoundly hearing-impaired children who used conventional hearing aids. The study included 29 children with prelingual deafness who used the Nucleus multichannel cochlear implant (mean age at onset of deafness = 0.9 years; mean age at implantation = 5.7 years) and "Gold," "Silver," and "Bronze" hearing aid users. All of the children produced 10 sentences repeated after an examiner's spoken model. Recordings of children's productions were played to panels of listeners with no prior experience with the speech of hearing-impaired talkers. As in previous studies of speech intelligibility, the judges wrote down what they had heard the children say. Intelligibility scores for children using cochlear implants showed gradual improvement over time. Average speech intelligibility of the cochlear implant users remained low through the first two years postimplant but began to exceed scores from Silver hearing aid users after 2.5 years. After 3.5 to 4 years of device use, average intelligibility for the implant users was 40%, or roughly 20% higher than that of Silver hearing aid users. At all intervals, however, average scores for the cochlear implant users remained clearly below those of Gold hearing aid users by about 30%. Very similar results were reported by Robbins, Kirk, Osberger, and Ertmer (1995) for 61 users of the Nucleus cochlear implant; by Miyamoto, Kirk, Robbins, Todd, and Riley (1996) for 50 subjects; Miyamoto, Kirk, Robbins, Todd, Riley, and Pisoni (1997); and by Miyamoto, Svirsky, Kirk, Robbins, Todd, and Riley (1997).

A study of speech intelligibility reported by Dawson, Blamey et al. (1995) used sentences from McGarr (1983) and listeners who were clinicians (speech pathologists or audiologists). For the eleven subjects examined in this study, age at onset of loss ranged from congenital to 3;3 (years;months), duration of deafness from 5;10 to 20;1, age at implantation from 8;0 to 20;1, and duration of implant use from 0;7 to 3;4. Thus, all subjects were profoundly deafened before the age of four years, and all subjects received cochlear implants after the age of eight years. In all, 38 sets of sentences from the preimplant and multiple postimplant intervals were available for judgments by 12 listeners. Preimplant scores, expressed as percent keywords correct, ranged from 0% to 36%, and postimplant scores from 19% to 81%. Mean postimplant scores were significantly higher ($p < .01$) than preimplant scores, for both high and low context sentences, as well as overall.

The intelligibility of single words produced by 16 French children using cochlear implants was examined by Mondain, Sillon, Vieu, Lanvin, Reuillard-Artieres, Tobey, and Uziel (1997). These children were all prelingually deaf and had received Nucleus cochlear implants by the age of 3 years. The children were divided into four groups of four children each who had used implants for 1, 2, 3, and 4 years. Audio recordings were made of children naming 20 pictures of common words. These recordings were played to a group of college students with no experience listening to the speech of hearing impaired persons; the listeners heard each word once and wrote what they heard. Responses generated a percent correct score. The average score for those who had used implants for one year was 4.2%, for two years of use 30.7%, for three years of use 55.2%, and for four years of use 74.2%. Speech intelligibility thus appeared to be higher for subjects who had more experience with their cochlear implants.

The work done by Osberger and colleagues compared the intelligibility of cochlear implant users followed longitudinally to intelligibility scores obtained from hearing aid users at a single point in time. These comparisons did not take into account the increases in intelligibility that might be observed in hearing aid users over time. Follow-up studies by Svirsky (this volume) and by Miyamoto, Svirsky et al., (1997) expanded earlier work by analyzing a larger number of subjects and, more importantly, by making a comparison that took into account the effect of age at testing for all subjects (cochlear implant and hearing aid users). These studies found that the group of cochlear implant users under study (which was mainly composed of users of the MPEAK stimulation strategy) received as much speech intelligibility benefit from their device as Silver hearing aid users did from theirs, but not more. Svirsky also analyzed the correlation between speech intelligibility and open-set speech perception by cochlear implant users, in an attempt to explain the large inter-subject differences in intelligibility. These correlations were about +0.7, and they were highly significant, suggesting that at least part of the intersubject variability in intelligibility may be associated with differences in perceptual benefit among subjects. Cochlear implant users who perceive speech better may use their perceptual skills to improve their own speech production, bringing it more in line with the acoustic characteristics of the ambient language.

In a recent study, Svirsky, Sloan, Caldwell and Miyamoto (1998) assessed the speech intelligibility of 44 children who were representative of current demographics of cochlear implantation. In contrast to earlier studies, which had tested later-implanted children who had used a variety of stimulation strategies since initial stimulation (including some currently obsolete strategies), this more recent study examined children who were implanted before the age of 6 and had used a state-of-the-art strategy (SPEAK or CIS) since initial stimulation. The improvements in intelligibility shown over time by these children clearly exceed those previously observed in pediatric multichannel cochlear implant users. After 1.5 to 2.5 years of implant use, the speech intelligibility of the CI users in this study was similar to the levels of speech intelligibility predicted for Gold hearing aid users (those with PTAs between 90-100 dB HL). This new result suggests that all profoundly, prelingually deaf children may be considered potential implant candidates, at least when we consider the levels of speech intelligibility that they may achieve with and without a CI. Interestingly, the high levels of speech intelligibility by CI users with respect to HA users observed in this study are paralleled in comparative studies of speech perception by CI and HA users (Svirsky & Meyer, in press). Taken together, studies like these may provide support for the expansion of implantation eligibility criteria. In the future, pediatric implant candidates may include children with higher levels of residual hearing than those who receive implants today.

2.2. Phonology

Although overall speech intelligibility has high face validity as a measure of communicative abilities afforded by auditory prostheses, including cochlear implants, much of the research on speech production in children who use cochlear implants has been directed toward examination of phonological properties, that is, consonants, vowels, and suprasegmentals. There are a number of reasons for this. First, there appears to be a high correlation between phonological characteristics and speech intelligibility (Smith, 1975). Second, developmental norms for speech and language production have traditionally been couched in terms of phoneme-sized units rather than overall speech intelligibility (e.g., Stoel-Gammon & Dunn, 1985). Comparisons of the development of children who use cochlear implants with other populations, especially those with normal hearing, have thus been made on the basis of similar analytical units. Third, traditional speech production remediation is based on the articulation of individual sounds (Bernthal and Bankson, 1998), offering remediation targets that are clearly and narrowly defined (although there are a number of exceptions to this approach, e.g., “whole language” approaches such as that of Hoffman, Norris, & Monjure, 1990).

Kirk and Hill-Brown (1985) appeared in print some five years after commencement of clinical trials in children of the 3M/House single-channel cochlear implant. Speech production was examined both imitatively, using the Phonetic Level Speech Evaluation, and spontaneously, using the Phonologic Level Speech Evaluation; both procedures are from Ling (1976). In these procedures, both segmental and nonsegmental aspects of speech production were evaluated on a three-point scale (0 to 2) corresponding to that aspect's being produced not at all, inconsistently, or consistently. For imitative speech production, assessed nonsegmental skills were vocal duration, vocal intensity, and vocal pitch; segmental skills were vowels and diphthongs, simple consonants, word-initial clusters, and word-final clusters. For spontaneous speech production, the nonsegmental skills assessed were breath control, intensity control, pitch control, intonation, vowel duration, consonant duration, phrasing, and stress; segmental skills were vowels and diphthongs, simple consonants, word-initial clusters, and word-final clusters. Both preimplant and six-month postimplant imitative speech assessments were available for 39 children, and preimplant and six-month postimplant spontaneous speech assessments were available for 37 children. Preimplant and one-year postimplant imitative and spontaneous speech assessments were available for 17 children.

At six months postimplant, the children showed significant improvement on imitative nonsegmental aspects of speech, as well as on imitative production of vowels, diphthongs, and consonants; no significant improvements, however, were seen in imitative production of consonant clusters. There were similar improvements into the one-year postimplant interval. Younger children tended to exhibit greater improvements, as did those who used oral communication as opposed to total communication. For spontaneous speech, there was a similar general trend for improvement on production of both nonsegmental and segmental skills with increased cochlear implant experience. Six months after receiving implants, the group of children showed significant improvement in breath control, intensity control, and vowel and consonant duration. Segmental aspects that similarly improved were production of vowels, diphthongs, and consonants. Improvement on these aspects was maintained one year after implantation, with additional significant improvements on phrasing and stress. Although children aged two to five years at the time of implantation showed the greatest improvements from pre- to postimplant intervals, it was children aged 6 to 12 years who had better spontaneous speech skills generally. A third group of children, those aged 13 to 18 years, showed no significant increases or decreases.

As mentioned previously, Tobey, Angelette, et al., (1991) examined intelligibility in children who used the Nucleus multichannel cochlear implant prior to and one year after implantation. Additional protocols for this study included examination of imitative segmental and nonsegmental characteristics, using the Phonetic Level Speech Evaluation (Ling, 1976), as well as phonological skills, using the Phonologic Level Speech Evaluation (Ling, 1976). The numeric values developed by Kirk and Hill-Brown (1985) were used for scoring, as well as categories of clinical significance from Tobey, Staller, Brimacombe, and Beiter (1988). Results indicated that 79% of the children studied improved on at least one third of the measures. Improvement was most common on tasks assessing imitative segmental characteristics (66.7% of the children), followed by tasks from the Phonologic Level Speech Evaluation (55.6%) and imitative nonsegmental characteristics (31.1%).

Similarly, Tobey and Hasenstab (1991) administered both the Phonetic Level and the Phonologic Level Speech Evaluations to 78 users of the Nucleus device once preoperatively and up to four times postoperatively (6, 12, 18, and 24 months postimplant). Results indicated improved performance on the nonsegmental subtest of the Phonetic Level Speech Evaluation with increased use of the implant. Differences in nonsegmental measures were significant between the preimplant interval and postimplant intervals, but the differences between individual postimplant intervals were generally not significant. In contrast, not only did performance on the segmental subtest of the Phonetic Level Speech Evaluation increase significantly from preimplant to postimplant, but the increases in performance between the various postimplant intervals were also significant.

Tobey, Pancamo, Staller, Brimacombe, and Beiter (1991) conducted a more fine-grained analysis of consonant production in 29 children before fitting with a Nucleus device and again after one year of device use. Using transcriptions of videotapes of speech samples, Tobey, Pancamo et al., (1991) constructed occurrence matrices for phonemes produced by each child at each interval, indicating manner, voicing, and place distinctions. Children were divided into four age groups: less than 5 years (*n* = 6), 6 to 8 years (*n* = 7), 9 to 11 years (*n* = 8), and 12 years and older (*n* = 8), in order to examine consonant production as a function of age. Preliminary results indicated that, across test intervals, place, and voicing, there was a significant effect of age on the production of all manner categories, such that a significantly greater percentage of children from the oldest age group produced stops, fricatives, glides, and nasals, relative to the three younger groups. Across place and voicing, a significantly greater proportion of children of all ages produced all manner categories after implantation than before implantation. Across testing intervals, the children produced more voiced stops than voiceless stops, and a greater number of more visible stop consonants (bilabials) were produced than less visible ones (alveolars and velars). Conversely, voiceless fricatives were produced by significantly more children than voiced ones, with labiodentals produced more than other places of articulation.

It should be noted that children without cochlear implants may also show some improvements on the variables just discussed. Ultimately, it would be important to assess the improvement that is due to the implant alone, and not to maturation. To this end, other recent studies have introduced the use of control data from other populations (e.g., children using other sensory devices). Tobey, Geers, and Brenner (1994) analyzed the speech production skills of three groups (users of cochlear implants, tactile aids, and hearing aids) of 13 children matched by age, hearing loss, intelligence, family support, and speech and language skills (Geers & Moog, 1994). All children had better ear PTA thresholds of 100 dB HL or greater (cochlear implant users had an average unaided threshold of 118 dB HL; both tactile aid and hearing aid users had an average unaided threshold of 110 dB HL) and were tested once a year for three years in both imitative (*CID Phonetic Inventory*; Moog, 1989) and spontaneous speech tasks. In addition, thirteen children with PTAs between 90 and 100 dB HL were tested once at the end of the study for comparison with the other three groups. For imitated speech production, all groups at the beginning of the study had similar scores, ranging from 23% to 27%, but after three years of device use and training, children using tactile or hearing aids had improved 20% on average, whereas those using cochlear implants improved by 36%. All three groups improved during the first year, but by two years into the study, there were significant differences between groups, such that cochlear implant users performed significantly better than users of tactile and hearing aids. The fourth group, hearing aid users with PTAs in the 90-100 dB HL range, were tested only at 36 months; their performance was significantly better than that of tactile aid and other users of hearing aids, but was not better than that of cochlear implant users, except in imitative production of suprasegmental characteristics. By the three-year interval, average subtest scores for the users of cochlear implants exceeded 70% for vowels and diphthongs, initial and final consonants. Assessment of spontaneous speech involved a comparison of the total number of sounds produced by a child with the total number of sounds that were correct. For both vowels and consonants, initial scores for all three groups were similar, ranging from 39% to 45%. Over three years, however, the improvements demonstrated by cochlear implant users outpaced those of tactile aid and hearing aid users. For consonant production, scores for cochlear implant users were significantly higher than those for tactile aid and hearing aid users. For individual consonant features, all three groups were observed to increase production of correct bilabials and alveolars, but only cochlear implant users improved production of velars; none of the groups increased production of palatals. After three years of device use, the cochlear implant group showed similar performance to the children with PTAs between 90 and 100 dB HL.

The relation between the Phonetic Level Speech Evaluation (Ling, 1976) and spontaneous speech was examined by Tye-Murray and Kirk (1993). In this investigation, Tye-Murray and Kirk correlated vowel and diphthong production by pediatric users of cochlear implants on the two measures. They concluded that although the Phonetic Level Speech Evaluation was an appropriate indicator of speech development and guide for remediation, it was only a weak predictor of vowel and diphthong production in spontaneous speech. Studies such as this one provide a cautionary note regarding generalization from specific tasks to speech production in general.

Kirk, Diefendorf, Riley, and Osberger (1995) compared consonant feature production in CV syllables by 24 multichannel cochlear implant users at two intervals and further compared this with production by two groups of hearing aid users (16 children whose mean unaided PTA was 103 dB HL and 16 children whose mean unaided PTA was 94 dB HL). Cochlear implant users demonstrated significant improvements in the production of voicing, place, and manner features after approximately 2.6 years of device use. Additionally, both cochlear implant users and hearing aid users with a mean PTA of 94 showed significantly better place and voicing scores than did hearing aid users with a mean PTA of 103.

Two recent studies have compared the consonant and vowel production of cochlear implant users and vibrotactile aid users. Ertmer, Kirk, Sehgal, Riley, and Osberger (1997) examined longitudinal changes in imitative vowel and diphthong production in 10 children using cochlear implants and 10 children using tactile aids. Production was evaluated at two intervals: (1) before children received a cochlear implant or tactile aid and (2) after at least one year of using the sensory aid (M = 1.8 years). From the earlier interval to the later interval, cochlear implant users showed significant improvement on seven of nine vowel and diphthong production measures, whereas the tactile aid users significantly increased performance on only one measure. Additionally, at the postdevice interval, cochlear implant users had significantly higher scores than the tactile aid users on eight of the nine measures. Sehgal, Kirk, Svirsky, Ertmer, and Osberger (1998) examined imitative consonant feature production in CV syllables by cochlear implant users and vibrotactile aid users. Both groups were tested before receiving their devices and again approximately 1.5 years after receiving their devices. Users of both cochlear implants and tactile aids showed relatively poor production of voicing, place, and manner features at the predevice interval. Both showed improved production postdevice, but the improvement demonstrated by the cochlear implant users was significantly greater than that of the vibrotactile aid users. Cochlear implant users improved performance on one place feature and all of the manner features.

2.3. Acoustics

Although studies of speech intelligibility and phonological development are important to assess the effectiveness of cochlear implants in children, it is also important to analyze the speech acoustics of these children to determine the underlying reasons for their individual differences in speech intelligibility and their ability (or lack thereof) to produce the different sounds of their ambient language.

One acoustic parameter that is important for distinguishing voiced and voiceless consonants is voice onset time (VOT), the interval between consonant release and the beginning of voicing. Producing appropriate VOT values requires the coordination of glottal and supraglottal articulators. Voicing-dependent differences in VOT represent an acoustic and articulatory contrast that is difficult for children with profound hearing impairment to produce. Tobey et al. (1995) measured VOT production in 18 French children who had used implants for at least two years. Measurements were made with the implant on and off. The two most interesting results from this study were that when the speech processor was on subjects produced more appropriate VOT, and that the VOT *contrast* between voiced and voiceless consonants was more pronounced. These results are consistent with an earlier study by Fourakis, Geers, and Tobey (1994) showing increased VOT contrast after two years of cochlear implant use for a group of prelingually deaf children.

Improvement in acoustic parameters when the speech processor was turned on has also been observed in studies of children's vowel formants (Murchison and Tobey, 1989; Tobey, Angelette et al., 1991; Tobey, 1993). Following the protocol initially used by Svirsky and Tobey (1991) with adults, ten children produced the word "head" in four successive blocks: with the implant on; immediately after turning it off; 20 minutes after it was turned off; and immediately after the implant was turned back on. The word "head" was chosen because a clear effect had been shown in the Svirsky and Tobey study for postlingually deafened adults. As in that study, second formant values produced by the speakers were significantly different in the "on" and the "off" conditions. The average second formant value for the vowel under study for children with normal hearing is 2610 Hz (Peterson and Barney, 1952). The "on" value in this study was above 2400 Hz while the "off" value was under 2000 Hz. Therefore, second formant values were much closer to the center of the normal range when the speech processor was turned on. With the processor off, vowel production became more neutralized, i.e., formant values were closer to those of the neutral vowel (1590 Hz). Could these on-off changes be indirect consequences of changes in other parameters, such as SPL, fundamental frequency (F0) or speaking rate? The first two are not at all likely, because there is no physical linkage between production of F2 and SPL or F0 that could explain an F2 change, particularly one of this magnitude. In addition, Tobey and her colleagues did measure F0 in this study and found no systematic on-off differences. Finally, speaking rate is indeed one acoustic parameter that may be physically linked with formant values. When speaking rate goes up, vowel duration decreases proportionally and there is less time for the articulators to reach their goals. In acoustic terms, this means that vowels become more centralized. Were the more central values of F2 with the speech processor off due to a rate increase? Quite the opposite: vowel duration was also measured in this study and it was found that it was more than 100 ms *longer* when the speech processor was off than when it was on. In other words, the increased articulatory accuracy when the speech processor was on was achieved not as a consequence of changes in speaking rate, but in spite of those changes.

Tye-Murray, Spencer, Bedia, and Woodworth (1996) cautioned that the acoustic changes that occur in on-off experiments may not necessarily result in a different phonetic percept. In other words, even when an acoustic parameter shows statistically significant differences in the "on" and "off" conditions, these differences are not necessarily perceptually salient to a listener. In this study, children with cochlear implants spoke a speech sample after having their speech processor off for several hours, and spoke it again after turning their speech processors on. Productions were analyzed using narrow transcriptions by speech-language pathologists. On average, it was found that there was no statistically significant difference between conditions on indices of vowel height, vowel place, initial consonant place, initial consonant voicing or final consonant voicing. The authors suggested that the acoustic differences in Tobey et al.'s studies are probably subtle. They further pointed out that some acoustic differences may be secondary consequences of changes in speaking intensity. However, acoustic theory explains how the vocal tract transfer function is governed largely by articulator position and lacking changes in articulator position, formant values can be only marginally influenced by changes in the voicing source. In other words, changes such as the F2 difference of more than 400 Hz observed by Tobey et al. cannot be explained by differences in vocal intensity. What else, then, could account for the apparent discrepancy between the results of Tobey et al. and those of Tye-Murray et al.? Tye-Murray et al. did not perform any acoustic studies of their subjects' productions, and Tobey et al. did not perform narrow transcriptions of theirs, so the possibility remains that subjects in the Tye-Murray et al. study did actually show smaller on-off acoustic differences than Tobey et al.'s. A more definitive understanding of these results must await future studies combining phonetic transcriptions, acoustic analyses and perhaps intelligibility measures.

Acoustic changes in the speech of children with cochlear implants are not limited to on-off differences. Economou, Tartter, Chute, and Hellman (1992) recorded and analyzed the speech of a postlingually deafened preadolescent during use of a single channel cochlear implant, on two occasions after it failed (1 day and 18 days post-failure), and on three occasions after reimplantation with a Nucleus-22 multichannel device (1 day, 6 months and 1 year post-reimplantation). The vowel space was initially somewhat constrained along the F2 dimension (when the subject used a single channel device), and showed severe neutralization after failure of the single channel device. After reimplantation, the vowel space expanded systematically, and the formant values obtained one year after reimplantation were the most closely aligned with normative values. Differences were also observed in consonant production. For example, initial voicing differentiation improved after Nucleus stimulation, and VOT for voiced stops shortened with respect to voiceless by 1 year post-reimplantation. However, there were exceptions to the overall normalizing trend. Some of these exceptions were the abnormally long closures, as well as increased aspiration and frication durations that were observed during the year of Nucleus stimulation.

In summary, the acoustic changes observed longitudinally or using on-off paradigms in pediatric cochlear implant users are generally, but not always, in the direction of more normal speech production when the speakers are receiving acoustic information from their devices.

2.4. Physiology

As we have indicated above, profound hearing impairment in early childhood affects speech intelligibility and the development of phonological systems. Children with early hearing impairment cannot master the control mechanisms used for speech production in the same way that their normal-hearing peers do. Inappropriate mastery of speech production skills, as well as possible improvement in these skills after cochlear implantation, can be measured instrumentally with studies of the child's acoustic output (as discussed in the previous section) and also with studies of the physiology of speech production. In this section we discuss two types of physiological studies, dealing with control of oral-nasal balance and intraoral pressure.

2.4.1. Oral-nasal balance

Inappropriate control of oral-nasal balance is considered to be an important characteristic of the speech of profoundly deaf individuals (Hudgins and Numbers, 1942; Angelocci, Kopp, & Holbrook, 1964; Colton and Cooker, 1968; Stevens, Nickerson, Boothroyd, & Rollins, 1976; Leder and Spitzer, 1990). The most apparent explanation for the presence of hypernasality in deaf speakers is that velopharyngeal closure is either not achieved or not maintained during speech. The control of velopharyngeal closure may be particularly difficult to learn for deaf children because it involves no visible feedback and very little tactile or proprioceptive feedback. Accordingly, it is probable that the development of vocal tract configurations related to the control of oral-nasal balance (or nasalance) is hindered by the lack of auditory feedback.

Although the control of oral-nasal balance is particularly difficult for profoundly deaf children, there have been frequent unpublished clinical reports of improvement in nasality when profoundly deaf children receive cochlear implants. These reports received objective verification in a study by Svirsky, Jones, and Osberger (1996a) and Svirsky and Jones (in press), which reported improvement in oral-nasal balance when pediatric cochlear implant users could hear their own speech. In this study, nasalance was measured from cochlear implant users with their implants turned on and off. This paradigm aimed to assess the short-term nasalance changes that may be observed a few minutes after the implant has been turned on or off, rather than the long term nasalance changes that may occur over the first few days, weeks or months after cochlear implantation. This on-off paradigm was first used by Svirsky and Tobey

(1991) in an acoustic study of vowel production by adult cochlear implant users, and was first applied to children by Murchison and Tobey (1989) (see above). Additional acoustic and physiological studies in adults (Svirsky, Lane, Perkell, & Wozniak, 1992; Matthies, Svirsky, Perkell, & Lane, 1994) are discussed in the second part of this chapter.

The subjects in the Svirsky et al. study were seven children with cochlear implants, selected for their ability to understand instructions and read fluently the elicitation materials. Subjects were tested once with their speech processors turned on, and a second time after one hour of auditory deprivation with their cochlear implants turned off. They read three passages (one with a high proportion of nasal consonants, one with no nasal consonants, and a "mixed" passage with both nasal and oral consonants) while the ratio of nasal and oral acoustic energy was measured with a Nasometer 6200 (Kay Elemetrics Corp.). To obtain normative data, and to assess the test-retest reliability of this protocol, an additional six children with normal hearing were tested. Tests on the normal-hearing subjects were performed twice, with a one-hour interval in between, to simulate the timing (but not the presence or absence of auditory signals) of the on and off conditions used with the cochlear implant subjects. These data provided the "normal" range against which the cochlear implant data were compared.

Cochlear implant subjects showed various patterns of abnormal nasal balance in the implant-off condition, with values that were sometimes above and sometimes below the normal range, depending on the sentence set and the individual subject. Generally, nasalance values were closer to the normal range in the implant-on condition. This was still true when only the on-off differences that were statistically significant were considered (indicated with asterisks in Figure 1): with only one exception, the significant on-off differences were in the direction of the normal range when the cochlear implant was on. With respect to the whole group of cochlear implant users, on-off differences were significant for the nasal sentences and for the oral sentences. Again, nasalance values averaged across the whole cochlear implant sample were closer to normal when the cochlear implant was on.

Insert Figure 1 about here

It is interesting to examine the individual performance of cochlear implant users in this study. Subjects CI1-CI5, who used multichannel cochlear implants and had acquired hearing losses (at 1.8 years for CI5, and after the age of 3 for the others) showed significant differences in nasalance between the on and the off conditions for at least one of the sentence sets. On the other hand, CI6 (who was congenitally deaf) and CI7 (who used a single channel device) did not show any differences between the two conditions for any of the sentence sets. Although these data are insufficient to permit any firm conclusions, they do suggest that in order to improve production of nasalance based on the input provided by a cochlear implant there may be at least two prerequisites. First, the cochlear implant user may need to have had access to spoken language during critical periods for language development, allowing the development of an internal model of speech articulation, and second, the input provided by the implant needs to be rich enough to recalibrate that internal model, and thus achieve the desired articulatory targets.

What are the underlying reasons for the normalization of nasalance values observed in this study? At least two hypotheses need to be considered. The "feedback" hypotheses postulates that self-hearing allows children to calibrate the articulatory strategies used to control nasalance. Thus, control of nasalance with the cochlear implant off may be less precise and results in values either above or below the normal range. With the cochlear implant on, subjects may be able to hear some acoustic correlates of nasalance and detect discrepancies between intended and actual values of those acoustic parameters. Following detection of a discrepancy, they re-calibrate the articulatory strategies involved in nasalance control. An alternative, more complicated hypothesis (the "indirect" hypothesis), is that the observed changes in nasalance are an indirect consequence of intentional changes in *other* articulatory parameters. As we discuss below, the cochlear implant has been shown to have a normalizing effect on a number of articulatory parameters, including sound pressure level (SPL), fundamental frequency (F0), breathiness, formant frequencies, spectra of sibilant sounds and various suprasegmental parameters related to intonation and stress (Svirsky and Tobey, 1991; Svirsky et al., 1992; Perkell et al., 1992; Matthies et al., 1994; Miyamoto et al., 1992, 1996; Osberger et al., 1993; Kirk et al., 1995; Tye-Murray, Spencer, & Gilbert-Bedia 1995; Tye-Murray, Spencer, & Woodworth, 1995; Dawson et al., 1995; Tobey and Geers, 1995). Some of these parameters may have an effect on measured nasalance. For example, cochlear implant users have been shown to speak more softly when their speech processors are turned on (Svirsky et al., 1992), and it is possible that a reduction in SPL might be associated with somewhat different amounts of reduction in oral and nasal energy. In other words, an intentional change in SPL would cause an indirect change in nasalance.

Although the data in Figure 1 are not sufficient to clearly support one explanation over the other, the "indirect" hypothesis does not seem to provide a good explanation for subjects CI3 and CI5's data, because their nasality changes when the speech processor was on instead of off went in different directions for different sentence sets. More specifically, subject CI3 had *higher* nasalance values in the on condition than in the off condition for the mixed sentence set, but *lower* in the on condition than in the off condition for the nasal and oral sentence sets. Similarly, subject CI5 showed *lower* nasalance in the on condition than in the off condition for the mixed sentence set and *higher* nasalance in the on condition than in the off condition for the nasal sentence set. If the indirect hypothesis indeed cannot explain all the on-off changes, we may have to conclude that the changes were at least *partly* due to the children's use of the auditory signal to improve their control of nasalization (the feedback hypothesis).

2.4.2 Intraoral pressure

Intraoral air pressure is the pressure that builds up behind an oral occlusion, for example, prior to the release of a stop consonant. In normal speakers, this parameter of speech production assumes very distinct values for the two members of a voiced-voiceless cognate pair of sounds, for example, voiceless /p/ vs. voiced /b/. The production of bilabial stops is an easy task for adult speakers, but it requires the coordination of glottal, supraglottal, and subglottal muscles, resulting in characteristic ranges of intraoral pressure. The production of an intervocalic English /p/, for example, requires all the following actions: closing the lips while abducting vocal folds (to end voicing); keeping the vocal tract walls stiff during closure (to allow a burst after the release); achieving intraoral pressure of 8-10 cm H_2O (to allow an appropriate post-release burst); and finally releasing the closure (producing a burst) while simultaneously starting to adduct (bring together) the vocal folds at such a rate that voicing starts at least 50 ms after the burst. The total closure duration should be about 180 ms (Subtelny, Worth and Sakuda, 1966). Production of an intervocalic English /b/ has the added complication that voicing needs to be maintained after vocal tract closure, and this requires a minimum pressure difference across the glottis (about 2 cm H_2O). However, maintaining this pressure difference is made difficult by the rising intraoral pressure caused by incoming air into the closed vocal tract. To maintain voicing during an intervocalic /b/, speakers close their lips while keeping the vocal folds adducted, and they use a combination of vocal tract wall relaxation and active vocal tract expansion to prolong voicing throughout closure. An intraoral pressure of 4-6 cm H_2O must be achieved, with total closure duration lasting about 140 ms. Voicing should start 0-20 ms after the burst. (Stevens and Klatt, 1974).

Children with normal hearing develop a speech production model, a model of the acoustic consequences of their articulatory actions. This model allows them to produce appropriate articulation and normal speech. On the other hand, children with cochlear implants may develop speech production models that are incomplete, and that may depend on the nature of the special auditory signal that they receive. Svirsky, Jones and Osberger (1996b) conducted a study to explore the ability of deaf children with cochlear implants to produce intervocalic bilabial stops. In particular, two parameters were explored: one whose acoustic consequences are well conveyed by the cochlear implant (closure duration) and another whose acoustic consequences are more difficult to perceive by cochlear implant users (peak intraoral pressure during closure). Peak intraoral pressure and closure duration during thirty repetitions of the words “puppy” and “baby” were measured in four profoundly-to-totally deaf children with cochlear implants. Measurements taken with the speech processor on and off were compared to normative values obtained from children with normal hearing. For all subjects (with or without cochlear implants) and both conditions (implant on and implant off), closure duration was significantly longer for /p/ than for /b/. In general, the cochlear implant users did not show significant changes in closure duration between the implant-on and the implant-off conditions. The few exceptions were in cases when a cochlear implant user had closure durations that were longer than normal when the speech processor was off, and became close to the normal range when the speech processor was turned on. In summary, there were few on-off differences in closure duration and most subjects had values that were close to or within the normal range. Some subjects had closure durations that were longer than normal, and some of these longer durations were reduced when the speech processor was turned on. In this respect, turning on the speech processor had a normalizing effect on closure duration, just as it did for nasalance.

It is interesting to examine a parameter for which the auditory input provided by the cochlear implant did not have the expected normalizing effect (see Figure 2). In the on condition, peak intraoral pressure values for /p/ were lower and closer to normal, but pressure values for /b/ tended to be higher (and less normal). Perhaps the most counterintuitive result from this study was that all subjects showed appropriately higher intraoral pressure for /p/ than for /b/ when the implant was off, but that contrast disappeared or was even reversed when the implant was on. This result was statistically significant for each of the four individuals who were studied. In other words, even though intervocalic /p/ is produced with higher peak intraoral pressure than intervocalic /b/ by talkers with normal hearing, this was observed in our measurements of cochlear implant users only when the speech processor was turned off. One possible explanation is that children with cochlear implants modify their speech production by selectively exploiting the acoustic dimensions of the speech signal that are well conveyed by the implant. For example, it is possible that subjects reduced their average overall subglottal pressure in order to achieve more normal values of SPL, a parameter they have no difficulty perceiving. At the same time, they may have maintained or even increased the driving pressure for some words such as “baby” in which all segments are voiced. This may have been done to ensure that voicing (another acoustic parameter that is well perceived by implant users) is maintained throughout the /b/ closures. Whether or not these specific hypotheses are true, it is clear that turning on the speech processors of pediatric cochlear implant users causes changes in their speech production. Sometimes these changes are in the direction of more normal parameter values (as with nasalance, discussed above), but other times the changes may be away from the normal range. It is possible that maladaptive motor strategies may develop in pediatric cochlear implant users, particularly when the acoustic consequences of the new motor strategy are not perceptually prominent to the implant user.

Insert Figure 2 about here

Studies by Higgins, Carney et al. (1996) show that some deaf children with cochlear implants produce /p/ and /b/ with negative intraoral pressure (that is, with air going into the mouth rather than going out), which is inappropriate in normal English production. Interestingly, these aberrant productions seemed part of idiosyncratic phonological systems. For example, two of the children used negative intraoral pressures more frequently before low than high vowels; another child did it more frequently before front than back vowels; and two of the children presented this behavior more frequently for voiced than voiceless stops. Two of the children (one of whom was a much more proficient talker than the other one) were enrolled in a study of traditional articulation treatment and visual feedback treatment to correct the use of negative intraoral pressure. These treatments were more successful with the less proficient talker, prompting the authors to suggest that deviant speech behaviors should be treated "before they become part of functional phonological systems."

Taken together, all these studies of the physiology of speech production in deaf children show that they use strategies unlike those employed by their peers with normal hearing. The information provided by a cochlear implant seems to have a normalizing effect in some, but not all, the physiological parameters of speech production that have been investigated to date.

3. Speech Production by Adults Who Use Cochlear Implants

In this section we discuss the changes in speech production that may be expected in postlingually deafened adults after receiving a cochlear implant. These changes are substantially more subtle that those observed in prelingually deaf children, who must rely on the auditory information provided by the implant while they learn the sounds and phonological system of their language. Typically, adults who become profoundly-to-totally deaf after acquiring language do not show major deterioration in their ability to produce speech sounds or to speak intelligibly (Cowie, Douglas-Cowie, & Kerr, 1982). This suggests that the role of hearing in speech production is much more limited in adults than in children. In the following section we discuss the changes in the acoustics and physiology of adult speech production that are associated with the use of a cochlear implant. These changes are interesting for two different reasons. From a clinical point of view, they help determine the effectiveness of cochlear implants in adults, as it relates to their production of speech. From a basic scientific point of view, postlingually deafened adult users of cochlear implants provide an interesting paradigm for exploring the role of hearing in adult speech production.

3.1. Acoustics

The role of hearing as an input for the neural mechanisms that control speech production remains controversial. Results obtained with normal hearing listeners led some researchers to propose that speech production may be controlled by auditory feedback (Fairbanks, 1955). This hypothesis received indirect support from early studies with the Lombard effect, an increase in vocal effort in the presence of background noise (see Lane and Tranel, 1971, for a review), and from delayed auditory feedback, in which speakers become disfluent when they hear their own speech delayed by about 200 ms (Fairbanks, 1955). However, later studies argued against an active role for audition in the moment-to-moment control of speech production, at least at the level of individual phonemes. For example, Borden (1979) argued that auditory information about many English phonemes is received too late for the central nervous system to be able to correct ongoing phonemic speech gestures. Most investigators have

proposed that auditory feedback serves to calibrate other systems that control speech on a moment-to-moment basis (Zimmerman and Retaliatta, 1981; Cowie and Douglas-Cowie, 1983).

Interest in this issue motivated several studies of the acoustics of speech production in postlingually deafened adults with cochlear implants. Perkell et al. (1992) studied vowel production in four recipients of the Ineraid cochlear implant before implantation and at regular intervals after implantation. The measured parameters included F1, F2, F0, SPL, duration and “harmonic difference,” a correlate of voice breathiness. Overall trends toward normative values in several parameters were found, but this result was not universal and it was complicated by lack of perceptual benefit in one subject, and by earlier deafening in two other subjects. An important aspect of the results in this study (which parallels the study of nasalance by Svirsky et al., 1996a, see above) is that because speakers respond differently to deafening, their responses to processor activation also differ. Subjects with parameter values that exceed the upper normative boundary may show a decrease after processor activation while subjects with parameters that are lower than the lower normative boundary may show an increase after processor activation. Another important result from this study relates to the interactions among measured parameters. The authors not only studied the longitudinal changes in each parameter, but also the correlations between different parameters for each individual subject. A large degree of interdependency was found among different parameters, some of which may have been due to mechanical interactions among different articulatory adjustments. For example, an increase in speaking rate results in shorter phoneme duration, and the shorter duration may be associated with formant frequency changes because the speaker may not have enough time to reach a steady state target. In the Perkell et al. study, most of the longitudinal changes could be attributed to changes in the average settings of speaking rate, F0 and SPL, in conjunction with the general pattern of relationships among parameters. However, the authors also pointed out that some observed F2 realignment may be attributable to the reception of spectral cues, rather than to the average settings of rate, F0 and SPL. A more recent longitudinal study of vowel production by postlingually deafened adult cochlear implant users was conducted by Langereis, Bosman, van Olphen, & Smoorenburg (1997). Recordings of eleven Dutch vowels in /hVt/ context were obtained pre-implant, and 3 and 12 months post-implant with the speech processor on and off. They observed an increase in F1 and F2 range when the speech processor was on, a result that was more marked for some subjects who had relatively small formant ranges prior to implantation. In addition, vowel formants were closer to normative values at 12 months post-implant. One interesting contribution of this study was the measurement of vowel “clustering,” defined as the ratio of between-vowel variance of F1 and F2 frequency and the within-vowel variance of three tokens of the same vowel. Increased clustering was found at 12 months post-implant than at the other measurement intervals, suggesting increased ability to produce phonological contrasts between vowels.

Svirsky et al. (1992) studied three of the subjects in the Perkell et al. study, using an “on-off” paradigm. In each block of the experiment, subjects produced ten randomized repetitions of six vowels within a carrier sentence. There were five blocks: after 24 hours of auditory deprivation (i.e., the speech processor was turned off); immediately after turning the speech processor on; after at least 10 minutes of having the processor on; immediately after turning the processor off; and at least 10 minutes after the speech processor was turned off. In other words, the testing sequence was off-on-on-off-off. The same six acoustic parameters that were used in the Perkell et al. study were measured in this on-off study. Results for SPL (one of the six parameters) are shown in Figure 3. The symbols represent SPL values, averaged across all six vowels, for each individual at each testing block. The figure displays several trends observed in the study, not only for SPL but for the other acoustic parameters. There were very significant differences between blocks, particularly when speech processor status changed (i.e., on to off or off to on). Second, these changes were generally (but not always) consistent with the longitudinal changes observed in the Perkell et al. study. Finally, changes were generally faster and more pronounced when the speech processor was turned on than when it was turned off. This is a desirable feature in any system that requires calibration to improve its operation, and in the speech production system in particular: when auditory input is withdrawn, it takes time for the acoustic output parameters to drift from its ideal values, but return to the desired range is rapid once the input is restored. How quickly does this happen? This is difficult to assess, due to normal variability in speech production. However, Svirsky et al. observed that SPL changes seemed to occur within the first few utterances after turning on the speech processor.

Insert Figure 3 about here

The on-off experimental protocol had been used in a previous study of the speech of multichannel cochlear implant users (Svirsky and Tobey, 1991). This study investigated the influence of auditory information on speech production, and it was focused on vowel production . The first experiment contrasted vowel formant frequencies produced without auditory stimulation (implant processor off) to those produced with auditory stimulation provided by a Nucleus-22 device (processor on). Significant shifts in second formant frequencies were observed for intermediate vowels (such as those in the words “head” and “hid”) produced without auditory stimulation; however, no significant shifts were observed for the point vowels. Higher first formant frequencies occurred in five of eight vowels when the processor was turned on versus off. Taken together, results from this first experiment suggest that auditory information may play a role in the production of intermediate vowels. Point vowels, on the other hand, may be accurately produced with the help of orosensory (tactile and proprioceptive) feedback or with the use of quantal properties of the speech production system (Stevens, 1972). A second experiment contrasted productions of the word “head” under three conditions: processor on, processor off and single-channel. This third condition was introduced as a control, to obtain speech samples with auditory feedback, but using a signal that carried no spectral information and that was useless for the purpose of calibrating or correcting inappropriately produced formant values. This experiment revealed significant shifts in second formant frequencies between utterances produced in the “on” condition and the other conditions. No significant differences in second formant frequencies were observed between the single-channel and off conditions. These data suggest that auditory stimulation plays a role in vowel production (at least for some vowels, in some speakers), and that the formant frequencies produced by a speaker may be dependent on the type of information delivered by the implant.

The effect on speech production of the auditory signal provided by a cochlear implant is not limited to vowel acoustics. Matthies, Svirsky et al. (1994) studied the potential influence of auditory information in the production of /s/ and /Σ/ by four postlingually deafened adults with four-channel Ineraid cochlear implants. Analyses of the spectra of the sibilant sounds were compared for speech obtained prior to implant activation, after early implant use and after 6 months of use. In addition, the electrical output delivered by the Ineraid device (measured at each of the four electrodes) was analyzed with pre- and postactivation speech samples to explore whether the speech production changes were potentially audible to the cochlear-implant user. Results indicated that subjects who showed abnormally low or incorrect contrast between /s/ and /Σ/ preactivation, and who received significant auditory benefit from their implants were able to increase the distinctiveness of their productions of the two speech sounds. In a follow-up study (Matthies, Svirsky, Perkell, & Lane, 1996) the articulator positions of a subject with an Ineraid cochlear implant were measured with an electromagnetic midsagittal articulometer (EMMA) system with and without auditory feedback available to the subject via his implant. Acoustic analysis of sibilant productions included specific measures of their spectral properties as well as the F3 formant amplitude. More general postural characteristics of the utterances, such as speech rate and sound level, were measured as well. The shape and central tendency of /Σ/ was related to tongue blade position, but changes in the spectral contrast between /s/ and /Σ/ were not related to

changes in the more general postural variables of rate and sound level. These findings suggest that auditory feedback provided by the cochlear implant allows postlingually deafened adults to monitor their speech and maintain phonemic contrast between /s/ and /Σ/, and that this is a true effect rather than a byproduct of changes in postural variables.

Cochlear implantation affects not only the characteristics of segment production, but also the suprasegmental characteristics of speech. Langereis, Bosman, van Olphen, & Smoorenburg (in press) found that the range over which F0 changed while reading a standard text (the "F0 sway") was reduced post-implant for most subjects who had inappropriately large F0 sway pre-implant. Consistent with the Langereis, Bosman et al. (in press) results, Lane, Wozniak et al. (1997) found that three out of four postlingually deafened adults in their study reduced the variability of their F0 and SPL contours after implantation. The one subject who did not change significantly was the one with least contour variability pre-implant. In an interestingly complementary part of this study, Lane et al. also tested a subject whose hearing had been severely reduced following surgery to remove an auditory neuroma. This subject was tested before and after surgery. It was found that the variability of her SPL and F0 contours increased after her hearing loss, in complementary fashion to the results observed in cochlear implant users.

In summary, cochlear implantation has been shown to have a beneficial effect on the production of speech, including both segmental and suprasegmental aspects, by postlingually deafened adults. In addition, the study of speech production in this population has proven to be an exciting new paradigm to help fine-tune current theories about the link between speech perception and speech production in mature speakers.

3.2. Physiology

Given that several acoustic aspects of speech were found to be abnormal in profoundly postlingually deaf adults and that the use of a cochlear implant tended to have a normalizing influence, it is not surprising that several studies of the physiological parameters that underlie speech production reached conclusions that were similar to those in the acoustic studies. In this section we review longitudinal and on-off studies of speech breathing, speech aerodynamics and nasal balance by postlingually deafened adults with cochlear implants (the kinematic study by Matthies, Svirsky et al., 1996, was discussed in the previous section because it had a strong acoustic component but it may also be considered a physiological study).

Speech breathing is known to be severely disordered in congenitally deaf speakers (see, for example, Hixon,1973; Forner and Hixon, 1977). They tend to expend excessive amounts of air, and to start their sentences with lung volumes well below normal. Both of these factors force them to encroach on respiratory reserve volume to produce sentences, working against inspiratory recoil forces. These abnormal speech breathing patterns are accompanied by voices characterized as "breathy" or "harsh," and by low levels of intelligibility. Lane, Perkell, Svirsky, and Webster (1991) measured lung volume during speech production on three postlingually deafened adults before and after they received cochlear implants. Pre-implant, one subject had abnormally high levels of average airflow and the other two subjects had abnormally low levels. Post-implant, all values changed toward the normative range: the high one decreased and the low ones increased. The subject with high airflow was the only one who used respiratory reserve volume pre-implant, reflecting inappropriate control of speech breathing. However, this behavior was normalized post-implant, as the subject took advantage of his newfound economy of air expenditure. In summary, this study showed that abnormalities in speech breathing are not restricted to the prelingually deaf, and that cochlear implantation can have a beneficial effect in the control of speech breathing. The authors suggested that some of the acoustic changes that take place post-implantation may be mediated by the normalization of breath-stream mechanisms. In addition, they pointed out that inappropriate laryngeal valving was a prime suspect in the search for explanations of improper speech breathing. This explanation finds some support in a study by Leeper, Gagne, Parnes, and Vidas (1993), who observed changes in laryngeal resistance (among several other speech aerodynamics changes) in five adventitiously deafened adults who used the Nucleus-22 cochlear implant. The hypothesis about a link between laryngeal valving and airflow also found support in the close relation between average airflow and an acoustic measure of breathiness that was observed by Svirsky, Lane et al. (1992) in on-off studies and by Perkell, Lane et al. (1992) in a longitudinal study.

As indicated above, the abnormalities in the speech of postlingually deafened adults are subtle, much less extensive than those observed in prelingually deafened speakers. For example, a recent study of nasal balance (Langereis, Dejonckere, van Olphen, & Smoorenburg, 1997) showed that eighteen out of the twenty-one postlingually deaf cochlear implant users that were tested had pre-implant values that were within the normal range. However, nasalance for some of the individuals with high pre-implant values changed toward the normative values.

4. Summary

A substantial body of literature, part of which has been discussed here, shows that cochlear implantation has a beneficial effect in speech production. This effect is rather pronounced in the case of prelingually deaf children, many of whom develop intelligible speech with the help of the implant. This newfound ability to speak in a manner that can be understood by naive listeners has its foundation in the development of a phonological system, and is expressed in acoustic and physiological measures as well as in longitudinal and on-off experiments.

The changes in speech production by postlingually deafened adults when they receive an auditory signal from their cochlear implants are more subtle that those observed in children, but they are no less significant from a theoretical point of view. The literature that studies these adult speakers has provided, and will continue to provide, important insights into the workings of normal speech production and the relation between what we hear and how we speak.

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Figure captions

Figure 1. The left panel shows oral-nasal balance values for seven cochlear implant users with the implant on (filled bars) and off (unfilled bars) for three sets of sentences that require different amounts of nasality. Most of the significant differences (*) represent values that are closer to the normal range (determined from normal-hearing children, right panel) when the cochlear implant is turned on.

Figure 2. Peak intraoral air pressure for /p/ and /b/ with cochlear implant on and off for four cochlear implant users. All four subjects displayed appropriately higher pressure for /p/ than for /b/ with the cochlear implant off (unfilled bars). Paradoxically, with the cochlear implant on (filled bars) this contrast either disappeared (subjects S3 and S4) or was even reversed (S1 and S2).

Figure 3. Circles indicate average SPL values averaged across ten repetitions of six vowels. Filled circles indicate values obtained with the speech processor on, and unfilled circles are the values obtained with the processor off. The first "off" value was obtained after 24 hours of sound deprivation. Filled and unfilled triangles on the vertical axis indicate post-activation and pre-activation values (from Perkell, Lane et al., 1992). Error bars are the average of the six standard errors of the mean (one for each vowel). Thus, error bars represent the variability associated with a single vowel and do not include the effect of variability due to cross-vowel differences.