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Speech deterioration in postlingually deafened adults

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Postlingually deafened adults reading the Rainbow Passage differed from hearing-control subjects in producing greater pitch variability and mean pitch on stressed and unstressed vowels, greater fluctuations in pitch within sentences, less correlation of intrinsic pitch with vowel height and slower temporal parameters. When reading the Phonetic Inventory Sentences, they revealed less differentiation of place of articulation in fricative and plosive consonants. The present findings, taken together with those of longitudinal and implant studies, are applied to constraining models of the role of self hearing in the elaboration of speech.

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INTRODUCTION

Bilateral profound sensorineural hearing loss incurred in adulthood is a severe handicap for the patient; it is also an opportunity to better understand the role of hearing in maintaining the process of speaking, an understanding that can contribute to treatment and the development of better prostheses.

Normal speech production is a complex highly skilled motor act. The refinement and stabilization of speech motor patterns probably continues well into the teen-age years (Kent, 1976; Cowie et al., 1988). There are several ways in which those stabilized motor patterns may use sensory information in the control of movement. Sensory information about an evolving movement of an individual articulator may be used in a closed-loop manner for error correction of commands to muscles that directly control the evolving gesture. In a goal-directed multi-articulator movement, however, afferent information about the evolving state of one articulator may be used to adjust the control of concurrent component gestures of the other participating articulators (Abbs, 1986). Sensory information about evolving movements may also be used to adjust control parameters for future movements, that is, to "validate" current parameter settings and change them as necessary to achieve the goals of the synergism.

The early literature on the role of hearing in controlling speech most often assigned to auditory feedback a closed-loop or feedforward function in regulating ongoing articulation. In a review of that literature, Lane and Tranel (1971) presented evidence and arguments against that view. While auditory feedback may be used in a closed-loop fashion under some circumstances, we suggest that the literature on the effects of altering sidetone is most compatible with assigning to sidetone primarily a validational role, altering the parameters of articulatory programs as necessary so that the phonological goals of those multi-articulator synergisms are achieved. Zimmermann and Rettliata (1981) put forward a related hypothesis: " ... auditory and other information is

employed to recalibrate or retune the [speech] production system" (p. 177).

This general conclusion about the role of sidetone is consistent with the finding that postlingually deafened adults do not suffer massive deterioration in the quality and intelligibility of their speech following deafening (Cowie et al., 1982). It does not, however, speak to the issue of why some speech elements are much more robust following deafening than others. We may postulate that those elements showing the greatest degeneration, such as pitch (see below), require aural validation of their articulatory programs more frequently than those elements that show less degeneration. This speculation naturally leads to the question, why do some speech elements require more aural validation than others? Several factors may be involved.

First, some articulatory programs seem to have relatively more degrees of freedom. Consider the program that sets vocal fold tension to achieve phonological pitch goals such as lexical or sentence stress. Such a program may undershoot or overshoot pitch targets in the complicated process of achieving phonological intentions in the face of such diverse mechanical interactions as the effects of subglottal pressure, postural changes in the laryngeal scaffolding, varying degrees of adduction of the vocal folds, and perhaps supraglottal articulations. The routine that combines lip and jaw movement to produce bilabial closure, on the other hand, has fewer degrees of freedom since most configurations short of closure correspond to one phonological intention (continuant) and all configurations beyond closure correspond to another (stop). Stevens (1972) and Perkell and Cohen (1989) have argued that the latitude for error in articulatory movements is best evaluated in relation to their acoustic consequences vis-à-vis phonemic requirements.

A second possible factor determining which speech elements are validated by sidetone on a fast cycle is the accessibility of other channels of afferent feedback. Routines that have access to such nonauditory afferent information must still be validated but it is possible that they are less readily perturbed, for example, by postural shifts. Perkell (1980)

has suggested that articulatory goals are expressed in terms of somatosensory afferent information that arises from a variety of receptors in the production mechanism. Or perhaps these alternate channels of afferent feedback affect the control mechanism only under special circumstances. In either case, those articulatory programs that are relatively impoverished in somatosensory feedback may be the most labile and require the most recalibration by sidetone validation.

It may be somewhat simplistic to ask, for each deteriorated element separately, what information is lacking due to the absence (or degradation) of sidetone and how often must that information be supplied. This way of framing the question does not allow for complex interactions among the acoustic parameters of speech. Problems with the laryngeal control of the air stream during speech may underlie the commonly reported "breathiness" of postlingually deafened speakers, contribute to disturbances in pitch control and voicing, bring about more frequent breath pauses and thus lower speaking rates. Improper management of the breath stream may also contribute to anomalies in the production of fricative and stop consonants whose spectra depend in part on air volume velocities supplied to the supraglottal constriction (Stevens, 1971).

Thus, studies of the speech properties that deteriorate markedly and of those that deteriorate less or not at all after prolonged profound bilateral deafness in adulthood can illuminate the underlying control mechanisms in speech. Cowie et al. (1982) recorded the speech of 12 adults who were profoundly deafened at various ages from 5 to 18, and gauged their intelligibility by measuring how accurately a group of subjects with normal hearing could shadow their speech. The deaf speakers' intelligibility scores covered a range from 98%–8%. Cowie and Douglas-Cowie (1983) analyzed recordings for nine of their twelve subjects and found, notably, hoarse and breathy phonation, inappropriate intonation, hypernasality, vowel reduction and lengthening, excess stress, extensive omission of consonants with mid and back places of articulation, extensive substitutions involving the midgroup, affricate reduction, a tendency for the palatal fricative to supplant the others, and devoicing and intrusive voicing, especially of midstops and fricatives. They also compared their findings with an extensive set for prelingually deafened children (Smith, 1975) and found a surprising degree of congruence, although consonant errors were 75 times more common among the children than among their postlingually deafened adults (see also Sherrard, 1982).

Plant (1983) and Plant and Hammarberg (1983) examined the speech of three Swedish patients (ages 18, 18, and 59) with sudden hearing loss of long date and found a reduced range of voice pitch, abnormalities in stress marking, vowel reduction, and excessive articulation time and pause time. Phonetic ratings cited, in various speakers, monotonous intonation, breathiness, "pressed" voice quality, hypernasality, excess stress and cluster simplification (see also Plant, 1984).

Using cinefluorography, Zimmerman and Rettaliata (1981) studied tongue and jaw displacement during speech with a 34-year-old male deafened progressively in his teens.

He spoke highly intelligibly and made no phonemic errors; however, compared to a speaker with normal hearing, he showed longer voicing durations and utterance durations. The speaker's transitions from a vowel to an adjacent consonant were longer than normal but those from a consonant to the following vowel were not; this suggests to the authors that auditory feedback during speech may be more important in closing the vocal tract than in opening it. Deafness seemed to have affected the speaker's control of the dorsum of his tongue more than his coordination of his lips and jaw—perhaps, the authors speculate, because dorsum movements to vowel positions may be more like slow tracking movements than the more ballistic movements of the tongue tip and lower lip to consonantal constrictions; if so, the former may rely more "on slowly changing acoustic waveforms for information about the course of their movement" (p.

The studies just cited describe diverse phonetic consequences of profound deafening in adulthood; the more prominent features seem to be disorders of laryngeal control and of timing. There is, in addition, a growing body of investigations of the speech of postlingually deafened adults before and after they are equipped with cochlear prostheses and receive auditory stimulation, including some sidetone (see House, 1976, 1978; Banfai et al., 1984; Leder et al., 1987; Leder et al., 1986).

Kirk and Edgerton (1983) selected for detailed study of aided and unaided speech four postlingually deafened patients who showed improved speech with stimulation from a House singlechannel implant during an average of 4 years. The two males proved to have less variable and lower fundamental frequency aided than unaided but the females were more variable and had higher pitch aided than not. All pitch measurements in the aided condition were more like those obtained from normal hearing speakers than they were in the unaided condition.

Tartter et al. (1989) examined the speech of a 17-yearold female, deafened at age 6-1/2, who received a multichannel implant at age 16. Listeners rated the patient's speech as less breathy and more appropriate in nasality and intonation following stimulation. Acoustic-phonetic measurements revealed that the subject gained better control of stress, manner distinctions, and plosive and fricative spectra with her prosthesis.

Oster (1987) and Plant and Oster (1986) found more normal average fundamental frequency, pitch range, improved control of F0 and duration in emphatic stress and more normal rate following the use of a single-channel implant and adjunctive therapy. Ball and Faulkner (1989) also report more normal F0 range and less irregularity in glottal periodicity in eight deafened adults using a single-channel extra-cochlear implant that fed back the speaker's fundamental frequency (see also Englemann et al., 1981).

Taken together, the studies cited implicate a role for audition in regulating, directly or indirectly, several speech properties; notably, voice quality, voicing, aspiration, pitch, intonation, stress, tempo, nasality, and fricative and plosive articulation. It is also noteworthy that there is wide variation in the reported speech anomalies introduced by profound

deafening and in the consequences of reintroducing some hearing. The picture is clouded by the varying measures employed—ratings, transcriptions, and acoustic parameters and, in some studies, by the experimenters' knowledge of their patients' auditory capacities and the concomitant use of speech therapy. Nevertheless, it is probably correct to say that the literature available implicates particularly disorders of phonation and suggests that there may be systematic changes in supraglottal articulation as well.

The present study aims to confirm and clarify these trends; it examines the speech of three patients with late and relatively recent onset of profound binaural sensorineural hearing loss. These speakers received no therapy before the present experiment, although one speaker did receive some therapy between the first- and second-time sample. We examine (1) the control of fundamental frequency, which may represent a slow tracking movement with relatively large degrees of freedom and relatively poor access to alternate afferent feedback; (2) the production of English plosives and fricatives that may entail a more ballistic synergistic movement and relatively greater afferent feedback.

I. METHOD

A. Subjects

We recruited three profoundly, bilaterally, sensorineurally deaf subjects through their otologists who provided audiometric measures for their patients and confirmed that they had no known neurological disorders (a possible sequel to the disease or trauma causing sudden hearing loss). Puretone audiometry confirmed that all the deaf speakers had pure-tone average losses greater than 110 dB in each ear. There were two male and one female subject, aged 32, 73, and 63, respectively; they had been profoundly deaf for 1.5, 6, and 1.5 years, respectively. We also recruited three speakers with reportedly normal hearing who were matched in sex, dialect, and approximately in age (25, 62, and 53 years, respectively) to the deaf speakers. All the speakers were paid for their services, which required about an hour.

B. Procedure

The subject came to the speech clinic at Northeastern University, and was seated in an audiometric room (IAC). A Shur condenser microphone, connected to a Tandberg tape recorder in the control room, was positioned approximately 6 in. in front of the subject's mouth. We engaged the subject in conversation by writing on a "magic slate." First, we elicited spontaneous speech and then the subject read the "Rainbow Passage." After about a year and a half had passed, we asked each subject to return for a second paid recording session in which he or she read the Rainbow Passage and the Phonetic Inventory Sentences (Fairbanks, 1960).

The female deaf subject had received some hours of speech therapy between the first and the second recording session.

C. Measurement

Although speakers might be less guarded in their speech when chatting than when reading, we chose to analyze the recordings of the Rainbow Passage and Phonetic Inventory Sentences to facilitate comparing our findings with those from other studies, and because there do not seem to be appreciable differences, in pitch control at any rate, between oral reading and spontaneous speech (Horii, 1982; Leder et al., 1987). Timing, fundamental frequency and spectral measurements were made with the aid of a speech analysis and editing program (see acknowledgments) running on the PDP 11/44 computer in the psychology department at Northeastern University. The recordings were digitized at a sampling rate of 20 kHz with a 10-kHz low-pass filter and 10-bit quantization. To measure pause durations, sections of the Rainbow Passage stored on disk were displayed (a few words at a time) in amplitude by time on a monitor. An operator identified and measured sentential pauses by placing the left and right cursors of the time window on either side of a candidate pause, listening to the contents of the window, and adjusting the cursors iteratively.

To measure the fundamental frequency of vowel tokens, an operator listening to the output of the D/A converter located the word containing the vowel and then moved cursors in on the vowel duration itself. She avoided transitional regions at segment boundaries by listening to the vowel color, by examining the damped oscillations of the AC waveform, and by checking formant tracks for some tokens. Over the interval thus defined by the cursors, the program did a running fundamental-frequency analysis using a 25.6-ms full-Hamming window updated every 5 ms. The mean and standard deviation of this set of measures characterized the voice pitch of that token.

We selected seven tokens of the voiceless midfricative /s/ and of the back /š/ from readings of the Phonetic Inventory Sentences (recorded during the second time sample only). The operator placed the 25.6-ms sample window at midduration of the fricative segment and the program performed a fast-Fourier analysis. To determine the midpoint of the spectral slice thus obtained, a computer program divided each spectral amplitude, in steps of 1 Hz from 1–8 kHz, by the sum of the amplitudes, cumulated these normalized values and identified the spectral frequency that corresponded to 50% (cf. Jassem, 1979).

There are between two and five tokens each of the voiced plosives /b, d, g/ and between three and five of the voiceless /p, t, k/ in the Phonetic Inventory Sentences. In order to assess how differentiated the front- and midplosives were in the subjects' speech, we applied a simple static measure of the spectral shape of each burst, namely, the slope of the straight line that best fit the spectral peaks of that burst (see Blumstein and Stevens, 1979; Kewley-Port et al., 1983 for a discussion of some of the measurement issues). First, the operator located the associated burst on the speech waveform and placed the leading edge of the 25.6-ms analysis window at the start of the burst and an LPC spectrum was computed. (In a few cases, it was necessary to reposition the window in order to allow spectral peaks to surface that had been submerged by local irregularities,—e.g., adjacent F2

and F3 might be analyzed by the program as a spuriously high F2.) Next a regression line was fit to the values of frequency and amplitude of the spectral peaks, so that a slope (in dB/octave, usually based on three to six values) was associated with each token.

For the back plosives, the operator first identified the most prominent peak in the region of 1200 –3500 kHz. (If there were two prominent peaks in this range separated by less than 500 Hz, their amplitude and frequency values were averaged.) The spectral slopes from the prominent peak to the peak on each side were computed in turn. (In tokens in which the initial plosive was followed by /r/ an additional high-frequency peak intruded; in those cases, only the slope from the prominent peak to the lower frequency peak was determined.) The mean absolute value of the two slopes was assigned to the token as a measure of spectral compactness.

II. RESULTS

A. Pitch

Figure 1 presents mean coefficients of variation of fundamental frequency within the stressed and unstressed vowels of the Rainbow Passage (pooled over three speakers and two readings, approximately 150 determinations per mean). The deaf speakers were, on the average, 43% more variable in their pitch than their hearing counterparts (F = 37.4, df = 1, 15, p < 0.01). Indeed, 17 of the 18 sentences measured in the first reading had more variable pitch within vowels when uttered by a deaf speaker, as did 15 out of 18 sentences in the second reading, a year later. The second-time sample proved to be merely a replication of the first (F = 0.5).

Basically, the same picture emerges if we consider the

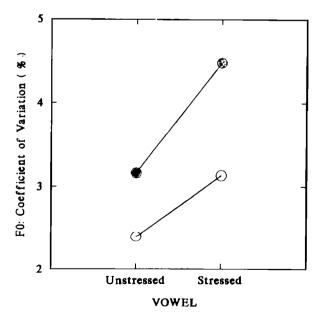


FIG. 1. Average coefficient of variation of fundamental frequency within the stressed and unstressed vowels of the Rainbow Passage. Three matched pairs of hearing (open symbols) and deaf speakers (closed symbols) read the passage twice at 1 year's interval. Each point is the mean of approximately 150 determinations pooled over the two time samples.

stressed and unstressed vowels separately. Figure 1 shows (and an ANOVA confirms) that deaf speakers used more variable voice pitch on both stressed vowels (F = 16.6, df = 1.15, p < 0.01) and unstressed vowels (F = 15.1, df = 1, 15; p < 0.01). Stressed vowels are more variable than unstressed vowels (F = 37, df = 1,15, p < 0.01) for both groups but the interaction between hearing status and vowel stress is significant: The pitch variability of the deaf speakers is particularly amplified by stress placement (F = 25.7, df = 1,15, p < 0.01). Specifically, the ratio of coefficients of pitch variation in stressed vowels to those in unstressed vowels was 1. 30 for the hearing speakers but 1. 42 for the deaf. The significant interaction between hearing status and the pitch variability associated with stressed syllables did not change from the first- to the second-time sample (F = 1.5, df = 1,15, p > 0.05). We found a corresponding significant interaction between hearing status and vowel stress for average voice pitch. Deaf speakers voiced stressed vowels with higher fundamental frequencies relative to their unstressed vowels than did their hearing counterparts (F = 46.4, df = 1,15, p < 0.01). There was no difference between the first- and second-time sample (F = 1.6, df = 1.15, p > 0.05).

The characteristic relation between pitch and vowel height (Ohala, 1978) was not present in the vowels uttered by our deaf speakers. We measured the mean fundamental frequencies of the vowels /i,i,e,æ,a,ɔ,u,,u, Λ / from the Rainbow Passage read by each of our speakers; depending on the vowel and speaker, there were between 1 and 12 tokens in each vowel mean. In order to compare these means with the values obtained for those vowels during readings of word lists reported by Peterson and Barney (1952), we computed the product-moment correlation for each of the six speakers between his or her mean F0 on each of the nine vowels and those of the sex-matched group in the Peterson and Barney study. The average correlation (pooling over both time samples) was 0.01 for the three deaf subjects and 0.52 for the hearing (Hotelling T = 2.2, df = 52, p < 0.05).

We have seen that the characteristically greater variability of the deaf speakers' pitch was exacerbated when they uttered stressed vowels. This variability turns out to be even greater when we examine their control of fundamental frequency while placing pitch prominence in sentences. Figure 2 presents the average coefficient of variation in fundamental frequency for the syllable in each sentence of the Rainbow Passage that had the highest average pitch; two-thirds of the time, this proved to be the syllable where the sentence stress would normally fall. (Each mean coefficient is pooled over six sentences and two time samples.) An ANOVA with hearing status, subject pair, and time sample as independent variables found the first two factors and their interaction significantly affected pitch variability on the prominent syllable. The pitch of the deaf speakers on this prominent syllable was more variable than that of their hearing counterparts (F = 11.9, df = 1,15, p < 0.01)—100 percent more in the first-time sample and 60% more in the second. Their relative pitch level was also greater (F = 13.5, df = 1,15, p < 0.01), as shown in Fig. 3, which presents the ratio of the mean pitch of the prominent syllable in each sentence to the average pitch of all the unstressed vowels in that sentence. (The

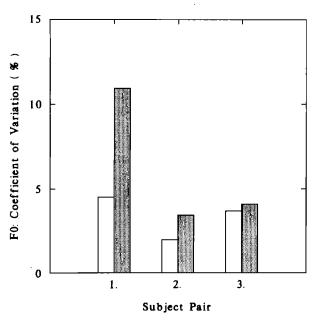


FIG. 2. Average coefficient of variation of fundamental frequency in vowels bearing pitch prominence in the sentences of the Rainbow Passage. The figure plots the standard deviation of F0 in the vowel bearing sentence stress divided by the mean F0 of that vowel. Each bar is the mean of 12 coefficients determined for each speaker, six in each of two time samples. Measures for deaf speakers are shown by closed bars.

mean ratios are based on six sentences and two time samples.)

Figure 4 reports on how much pitch changed from one vowel to the next within the sentences of the Rainbow Passage. It presents the coefficient of variation in F0 pooled over six sentences and two time samples. Once again, the deaf speakers proved more variable than the hearing (F=8.5, df=1,15, p<0.05).

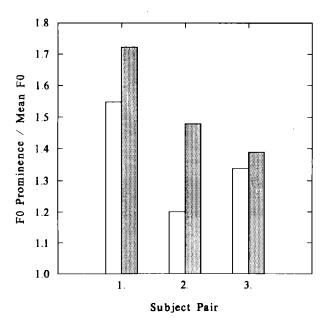


FIG. 3. The ratio of the mean pitch in the prominent syllable of each sentence to the average pitch of the unstressed vowels in that sentence. Each bar is the mean of 12 ratios determined for each speaker, six in each of two time samples.

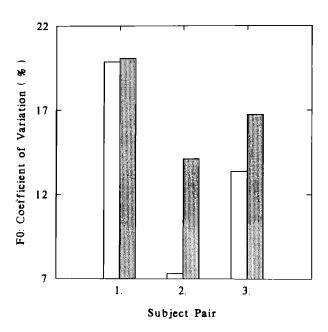


FIG. 4. The variation of fundamental frequency within sentences of the Rainbow Passage. For each of six speakers, a mean pitch was determined for each vowel, and the standard deviation of those means in each sentence was expressed as a percent of the average sentence pitch. These coefficients were averaged over six sentences and two time samples.

B. Fricative consonants

Our deaf speakers differentiated the voiceless palatal and alveolar fricatives in their speech but to a lesser degree than their hearing counterparts. Figure 5 shows average spectral midpoints. Those for the palatal fricative /š/ are reliably lower than for the alveolar /s/ (F = 54.3, df = 1,12, p < 0.01). However, there is a significant interaction between hearing status and fricative class (F = 29.3, df = 1,12, p < 0.01); it is due largely to an upward shift in the

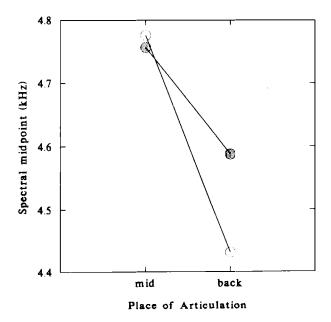


FIG. 5. The midpoints of spectral slices for /s/ and /š/ uttered by deaf and hearing speakers reading the Fairbanks Sentences. Each point is the mean of approximately 15 determinations, 5 per speaker.

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spectra of /s/ for the deaf speakers. To permit a more detailed comparison of fricative differentiation by our deaf and hearing speakers reading the Phonetic Inventory Sentences, we sorted the fricative tokens into four groups according to whether the following segment was a front- mid- or back vowel or the consonant /t/. Then we subtracted the average spectral midpoint of the /s/ tokens from that of the /s/ tokens in each of the four groups. For all pairs of subjects and all phonetic environments, deaf speakers differentiated the two fricatives less than the hearing speakers—170 Hz compared with 357 Hz (t = 6.3, df = 14, p < 0.01).

C. Plosive consonants

Our deaf speakers did not differentiate the plosive consonants in their burst spectra as much as their hearing counterparts did. Figure 6 presents the average spectral slopes for the diffuse falling (/p,b/), diffuse rising (/t,d/), and compact (/k,g/) plosives, voiced and voiceless segments pooled (seven determinations per speaker). The difference in spectral slope between the labial and alveolar consonants was 1.5 dB/octave for the deaf speakers, whereas that for the hearing speakers was 6.7 (F=19.7, df=1,4, p<0.01). The lack of place differentiation in the deaf speakers arises from their flat spectral slopes in the bilabial plosives. An ANOVA with a posteriori contrasts showed that the deaf speakers' spectral slopes were flatter on the labial plosives than those of the hearing (F=9.8, df=1,4, p<0.05) but not reliably different on the alveolar plosives.

Turning to the velar plosives, their spectral peaks were associated with an average slope of 6.8 dB/octave among the deaf speakers. Velar plosives were more compact among the hearing speakers where their spectral peaks had adjacent

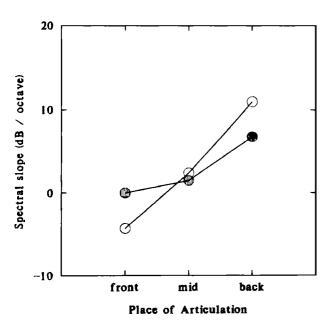


FIG. 6. The spectral slopes of the bursts of /p/, /t/, and /k/ and their voiced homologues, uttered by deaf and hearing speakers reading the Fairbanks Sentences. Each bar is the mean of approximately 21 determinations, 7 per speaker. (The values for the compact plosives are the average of the absolute value of the leading and trailing slopes about the spectral midfrequency peak; see text.)

slopes averaging 11.0 dB/octave but the difference was not reliable (F = 2.0, df = 1.4, p > 0.05).

III. DISCUSSION

The present study found evidence of marked disturbances in the fundamental frequency of the speech of postlingually deafened adults. Our speakers produced greater pitch variability and levels on stressed and on unstressed vowels, greater fluctuations of pitch within sentences, and an abnormal relation of intrinsic pitch with vowel height.

Additional evidence that profound deafness is associated with heightened pitch variability and average pitch levels comes from Leder, Spitzer and Kirchner (1987) who found that 21 postlingually deafened men with profound sensorineural losses bilaterally had a higher fundamental frequency when reading a sentence from the Rainbow Passage than did normally hearing age-matched men. They also report that subjects with profound deafness of more than 10 years demonstrated more variability of F0 than those with profound deafness of more recent date (also see Leder and Spitzer, 1990).

Two postlingually deafened adults in a study by Ball and Ison (1984) displayed marked irregularities in glottal period and one of them showed reduced pitch range pre-implant; after stimulation with the extracochlear implant supplying voice pitch, both parameters were more normal. Fourcin et al. (1983) report that their deaf subject's control of the range and regularity of her fundamental frequency improved markedly when they supplied her feedback about her voice pitch over a promontory electrode and adjunctive therapy. On the other hand, Waldstein (1989) had seven speakers deafened postlingually at ages ranging from 6 to 40 and hearing age-matched controls read lists of eight nouns in isolation and found less period-to-period variability in voice pitch among the deaf speakers.

Disturbances associated with deafness in the characteristic relation between vowel height and intrinsic pitch, reported above, have also been reported in two other studies. Plant (1984) found that a 14-year-old male deafened at age 11 by meningitis had normal vowel formant values but excessively high pitch associated with the high vowels. Angelocci et al. (1964) obtained a similar result with 18 teen-age congenitally deaf male speakers who, however, did not differentiate the vowels well by their second formants. The authors suggest that their subjects may have been using fundamental frequency to convey vowel identification, in compensation for their reduced formant ranges.

Our deaf speakers' control of fundamental frequency was particularly variable in placing sentence stress. In a related finding, Cowie *et al.* (1988) report that their deaf speakers placed relatively more pitch drops on the most prominent syllable in tone groups than did their hearing control subjects. (Also see Leder *et al.*, 1986.)

At the suprasegmental level, our deaf speakers showed heightened variability in mean pitch from vowel to vowel compared to the normal hearing control subjects. One of two late-deafened speakers in a study by Waldstein (1989) also revealed elevated pitch variability from vowel to vowel within sentences but the other deaf speaker did not. Plant and

Hammarberg (1983) report that this measure was normal in one late-deafened speaker of Swedish. The deaf subject showing the greatest variability in pitch and pitch prominence in Figs. 2–4 was the subject (male) with the longest period since onset of total bilateral deafness, 6 years. The sample size does not permit us to examine this variable. It is noteworthy that there were no significant changes in the speech parameters examined from the first- to the second-time sample, suggesting that deterioration of those parameters proceeds slowly in late-deafened adults.

From the literature cited earlier, it appears that the fricatives are a class of segments particularly vulnerable to deterioration following deafening. Figure 5 shows differences in mean spectral slope between our deaf and hearing speakers consistent with the hypothesis that the deaf subjects were articulating the palatovelar fricative with a more front place of articulation. Consistent with our findings, Tartter et al. (1989) report a tendency in their speaker for place of articulation to be displaced forward pre-implant. Cowie and Douglas-Cowie (1983), likewise state that the mid- and back-fricatives are the exception to the general trend of backward shift in the postlabial consonants. From their phonetic transcriptions, it is not clear if their speakers had restructured their phonological systems, decreasing the number of functional contrasts. The data presented in Fig. 5 throw light on this question for it appears that postlingually deafened adults continue to differentiate the two fricatives but merely less so, indicating that their deafness has led not so much to a change in phonological plans for this contrast as to a systematic error in phonetic implementation.

The burst spectra of our deaf speakers' plosive consonants were not as well differentiated by place of articulation as were those of their hearing counterparts. It is noteworthy that the articulation of bilabial plosives is visible in the speech of others (and indeed even in one's own speech) and is accompanied by tactile and proprioceptive stimulation; nevertheless, our deaf speakers produced those plosives with abnormally flat spectra. This outcome is consistent with the suggestion, made above, that some cases of speech deterioration following profound deafness may not be the direct result of a lack of auditory calibration of the execution of that particular speech element but rather the indirect result of articulatory anomalies in other interdependent speech elements. Tartter et al. (1989) report a general front tendency in the speech of their postlingually deafened subject which may be consistent with the spectral flattening of our deaf speakers' velar plosive consonants in some cases; however, the effect is not statistically reliable in the present sample. Working with perceptual rather than acoustic data, Cowie and Douglas-Cowie (1983) obtained a somewhat different result than the present study. Their phonetic transcriptions reveal labial plosives relatively unaffected in their deaf speakers and alveolar plosives replaced frequently by glottal stops.

It is noteworthy that the reduced differentiation of segmental contrasts in our deaf speakers was accompanied by an overall increase in the time of articulation (and of pausing) and thus is not mediated by a reduction in the time available to execute distinct articulatory patterns. The deaf speakers' average vowel duration in the Rainbow Passage was 98 ms while that of the hearing speakers was 86 (t=3.3, df=17, p<0.01). The total time spent pausing averaged 8.8 s for the deaf speakers and 5.7 s for the hearing. (a t test for matched pairs of total sentence pause times gave t=2.2, df=17, p<0.05.) Average pause durations per sentence for the two groups were 0. 74 and 0.58 s, respectively (t=2.3, df=17, p<0.05). Plant (1984) and Leder et al. (1987) have also reported slowing of speaking rate in deafened speakers compared to hearing controls. In congenitally deaf speakers, the reduction in speaking rate is attributable in part to an increase in inspiratory pausing (Whitehead, 1983).

We have presented evidence of anomalies in the phonatory, segmental, and suprasegmental properties of the speech of postlingually deafened adults. Pitch variability and pitch levels were augmented, temporal parameters were slowed, places of articulation were less differentiated compared to hearing counterparts. These trends, taken together with the findings of earlier studies, may implicate, inter alia, an underlying disorder of laryngeal control that is the consequence of profound binaural hearing loss in adulthood. Heightened pitch variability and pitch levels and abnormal relations between intrinsic pitch and vowel height are likely to reflect such physiological variables as contraction of muscles that regulate the length and adduction of the vocal folds and subglottal pressure. Changes in rate of articulation may also be linked to laryngeal valving of the breath stream. The anomalies we have found in fricative and plosive spectra among our deaf speakers may also be linked to this factor or they may reflect a distinct breakdown in the achievement of phonemic goals because of a lack of auditory validation. The global picture suggests that self hearing has a particular role to play in the management of laryngeal function during speech.

Our ongoing research is providing just such evidence that postlingually deafened adults mismanage the breath stream during speech and recover more normal control of speech breathing following a few weeks' stimulation from a cochlear prosthesis (Lane et al., 1990). We are now investigating whether such respiratory changes are associated with concomitant changes in the suprasegmental and segmental properties of speech.

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