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Changes in sound pressure and fundamental frequency contours following changes in hearing status

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Sound-pressure level (SPL) and fundamental frequency (F_0) contours were obtained from four postlingually deafened adults who received cochlear implants and from a subject with Neurofibromatosis-2 (NF2) who had her hearing severely reduced following surgery to remove an auditory-nerve tumor and to implant an auditory brainstem implant. SPL and F_0 contours for each phrase in passages read before and after changes in hearing were averaged over repeated readings and then normalized with respect to the highest SPL or F_0 value in the contour. The regularity of each average contour was measured by calculating differences between successive syllable means and averaging the absolute values of these differences. With auditory feedback made available, the cochlear implant user with the least contour variation preimplant showed no change but all of the remaining speakers produced less variable F_0 contours and three also produced less variable SPL contours. In complementary fashion, when the NF2 speaker had her auditory feedback severely reduced, she produced *more* variable F_0 and SPL contours. The results are interpreted as supporting a dual-process theory of the role of auditory feedback in speech production, according to which one role of self-hearing is to monitor transmission conditions, leading the speaker to make changes in speech postures aimed at maintaining intelligibility. © 1997 Acoustical Society of America. [S0001-4966(97)03304-3]

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BACKGROUND

There is a body of evidence from postlingually deafened adults and from users of cochlear implants that implicates a role for hearing in regulating average parameter values of speech sound-pressure level (SPL) and fundamental frequency (F_0). Leder *et al.* (1987b) reported that postlingually deafened men with profound bilateral sensorineural losses read at higher average SPL than did normally hearing males. Leder *et al.* (1987) reported that deafened men had a higher F_0 when reading than normally hearing age-matched men (also see Binnie *et al.*, 1982; Leder and Spitzer, 1993; Plant, 1984).

When some hearing has been restored to deafened adults by means of a cochlear prosthesis, reductions in average SPL and F_0 have been found. These parameters of the speech signal appear to be relatively well represented by the electrical stimulation delivered by the implant speech processor (cf. Shannon, 1993). Leder and Spitzer (1990) reported reduced speech amplitude, F_0 , and duration during readings of the Rainbow Passage by ten deafened adult males using single-channel implants. After only one day of prosthetic audition, their speakers reduced average F_0 significantly while subsequent reductions were smaller and not reliable. This indicates a relatively rapid change in F_0 with provision of auditory feedback. Oster (1987) also reported F_0 reductions with cochlear prosthesis use in two postlingually deafened adults, one male and one female, and Lane *et al.* (1994) obtained a

comparable result with two female implant users. However, Kirk and Edgerton (1983) found F_0 higher when comparing speech in aided to unaided conditions with two female speakers who had been using their implants for two and eight years. Both of these implant users had a lower F_0 unaided than the average of five hearing female control speakers, so the direction of change in this parameter with auditory feedback supplied appears to have been toward normal.

In a longitudinal study of vowel production by implant users, Perkell *et al.* (1992) also found reductions in SPL, F_0 , and duration of vowels following activation of the patients' implant speech processors. A companion study that introduced short-term changes in processor status obtained similar results (Svirsky *et al.*, 1992). In the longitudinal study, we observed informally that the reductions in average speech parameter values with auditory feedback available were accompanied by increases in the regularity of SPL and F_0 contours obtained for one speaker who read sentences from the Rainbow Passage during the same elicitation sessions in which she read a vowel inventory. However, studies of changes in F_0 contours with deafening and cochlear prosthesis have yielded apparently inconsistent results. Some studies report that the speech of postlingually deafened subjects is "monotonous" (Binnie *et al.*, 1982; Plant, 1983, 1984) and several have found restricted F_0 range (Plant, 1983; Plant and Hammarberg, 1983; Ball and Ison, 1984; Plant and Oster, 1986; Ball and Faulkner, 1989). In a finding that may be related, Cowie and Douglas-Cowie (1992) reported too little pitch movement to and from prominent syllables in tone groups.

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On the other hand, the findings of several studies point to increased variation of F_0 contours with deafening. Thus, Cowie and Douglas-Cowie (1983) found abrupt switches from low to high pitches in adjacent words or syllables uttered by postlingually deafened speakers and Lane and Webster (1991) found that such speakers produced the prominent syllable in each sentence with excessively high F_0 . Additionally, Leder *et al.* (1986) reported F_0 measures for contrastive stress in noun/verb bisyllables spoken by a deafened adult cochlear implant user. After four months of implant use, the speaker had improved the contrast between the nouns and corresponding verbs, and had reduced the average F_0 difference between the stressed and unstressed syllables within words.

The present study was aimed at clarifying the influence of auditory feedback on SPL and F_0 contours. Those contours were obtained from five speakers who underwent changes in long-term hearing status. Four speakers were postlingually deafened adults who had some auditory feedback restored with a cochlear prosthesis. In a complementary situation, a fifth speaker, a patient with Neurofibromatosis-2 (NF2), had her hearing severely reduced following surgery to remove an auditory-nerve tumor and to implant an auditory brainstem implant.

We have presented a dual-process theory of the role of hearing in speech production, based in part on our prior studies of changes in speech production by cochlear implant users (Perkell *et al.*, 1992; Svirsky *et al.*, 1992; Lane *et al.*, 1994; Matthies *et al.* 1994; Lane *et al.*, 1995). Briefly, auditory feedback serves to validate articulatory/acoustic relations that underlie synergisms for phoneme production. (Investigators of deafened adult speech who have advanced some form of validation hypothesis include Gammon *et al.*, 1971; Sherrard, 1982; and Waldstein, 1990.) In order to maintain intelligibility, auditory feedback also serves to monitor transmission conditions, leading the speaker to respond adaptively with changes in average SPL, F_0 , and syllable duration by implementing changes in underlying speech “postures,” such as the balance between expiratory and inspiratory forces associated with a subglottal pressure, average tension in and separation of the vocal folds, and speaking rate. We hypothesize that changes in the variability of SPL and F_0 contours reflect that same role of self-hearing; exaggerated SPL and F_0 inflections serve to enhance intelligibility under adverse transmission conditions. Therefore, we have compared each speaker’s contours obtained with auditory feedback (implant users after activation of their speech processors and the NF2 patient before hearing loss) to those obtained without feedback (preactivation for implant users) or with severely reduced feedback (postsurgery for the NF2 patient). A finding that contours obtained with auditory feedback are less variable than those obtained under reduced or absent auditory feedback would be consistent with this hypothesis.

I. METHOD

A. Subjects

Four of the five speakers in this experiment used cochlear prostheses. Prior to implant, all four had three-

frequency pure-tone average losses (at 0.5, 1, and 2 kHz) greater than 102 dB in each ear; therefore, we refer to their hearing status preintervention as without auditory feedback. Three of these four implant users were women (the same three women studied by Lane *et al.*, 1994).

The first subject with a cochlear implant, CFA,¹ had a monaural impairment in her left ear with onset at age 18. At age 33, she experienced a rapid hearing loss in her right ear and began wearing a hearing aid in her left ear. She discontinued hearing aid use at age 45, and was implanted at age 49.

Subject CFB had normal hearing until age 21 and bilateral progressive hearing loss. She used a hearing aid in her left ear from ages 23–40, whereupon that ear received a cochlear implant. She also wore a hearing aid in her right ear ages 31–39.

Subject CFC had a severe bilateral hearing loss with onset at age 2. She began using a hearing aid in her right ear at age 5 and in her left at age 29. She wore hearing aids until age 47, when she discontinued use because of dizziness. In the same year, she underwent implant surgery.

The one male implant subject, CMD, had a congenital bilateral loss. He began wearing a hearing aid in his right ear at age 3 and in his left at age 11. He wore these aids until age 36, when he discontinued use because of dizziness. In the same year, he underwent implant surgery. He was always tested in this research without hearing aids.

Subject NFA was diagnosed with Neurofibromatosis-2 (NF2) at age 17. NF2 is a genetic disorder that causes bilateral acoustic neuromas. Patients with this disease are at high risk of losing their hearing, usually due to the surgical intervention necessary to remove the tumor before it impinges on life-sustaining brain functions. At age 17, NFA had a right acoustic neuroma surgically removed, and suffered complete loss of hearing on that side. Over the next few years, she experienced a gradual progressive hearing loss on the left side caused by the growth of another acoustic neuroma. By age 20, she had a mild-to-moderate, fairly flat, hearing loss. She began wearing a hearing aid at age 22. By age 26, the loss was moderate and continued to increase slowly. At the time of our first baseline recording of her speech production, at age 27, she had excellent aided speech discrimination scores (above 90%, NU-6; Tillman and Carhart, 1966). At age 27, NFA had surgery for both the removal of her left acoustic neuroma and implantation of an auditory brainstem implant (ABI). During surgery, the auditory nerve had to be severed and there was damage to the left facial nerve, which caused a readily apparent left facial palsy. Her glottal function was observed with endoscopy to be normal following the tumor removal and ABI implantation. In all the postintervention recordings, NFA’s ABI was in operation. However, her speech discrimination scores with bilateral deafness and the ABI ranged from 0% to 4% correct between 3 and 15 months after surgery. Clearly, NFA’s access to acoustic information was severely reduced after her surgery, despite use of the ABI.

B. Prostheses

The Ineraid cochlear implant (Richards Medical Co.) consists of an implanted electrode array, a percutaneous pedestal and connector, and an external sound processor. The sound processor has an ear level microphone, a wideband automatic gain control, and four overlapping bandpass filters with crossover frequencies of approximately 0.7, 1.4, and 2.3 kHz. The four analog filter outputs are delivered individually (via the percutaneous connector) to four monopolar intracochlear electrodes, with a common return electrode. The electrodes, spaced approximately 4 mm apart, were positioned successfully in all subjects by insertion into the scala tympani through the round window, with the first placed most apically, some 22 mm from the round window. Although the speech processing strategy was the same for all implant users, there were user adjustments for input sensitivity and volume, and channel specific gains set by the clinician for each subject. During voiced segments, F_0 is represented in the sound pressure \times time waveforms coming from several channels of the speech processor by the periodicity of the complex waveform. The SPL is represented by the amplitude of those waveforms.

Subject NFA was surgically implanted at the House Ear Institute (Los Angeles, CA) with a multichannel version of the auditory brainstem implant (Brackmann *et al.*, 1993). The implant consists of an eight-electrode array placed on the cochlear nucleus, a receiver/stimulator providing transcutaneous electromagnetic signal transmission and an external microphone and signal processor. Subject NFA was fitted with a processor programmed to stimulate seven electrodes referenced to an indifferent electrode on the receiver/stimulator case (monopolar mode). An F_0 F_1 F_2 F_5 feature-extraction encoder was used to provide spectral, amplitude, and temporal information. In this processing strategy, F_0 is represented by the repetition rate of the pulse train applied to the stimulating electrodes which, in turn, are activated based upon the spectral characteristics of the input speech signal. The SPL is represented by the amplitude of these pulse trains.

C. Speech elicitation

Two baseline recordings of speech production were made prior to surgical intervention. Postintervention recordings were made repeatedly at variable intervals. The time elapsed between intervention and the two consecutive recordings analyzed for this study were, for both CFA and CFB, 1 and 2 yr; for CFC and CMD, 0.5 and 1 yr; and for NFA, 11 and 35 weeks.

The speech material consisted of readings of the Rainbow Passage (Fairbanks, 1960), read three times each for subjects CFA, CFB, and CFC, and five times each for subjects CMD and NFA. Other speech material was read for approximately 15 min between each reading of the passage.

D. Recording, calibration, and signal processing

The subject was seated in a chair in a sound-attenuating room. A small electret microphone was placed at a fixed distance of 20 cm in front of the subject's lips by attaching it

to a flexible arm affixed to the back of the chair. Lung volume was measured using a RespiTrace inductive plethysmograph (Ambulatory Monitoring, Inc.). The utterance materials were projected on a screen located several feet in front of the subject. For calibration of sound-pressure level, at the start of each hour-long recording session, a sound source (electrolarynx) was placed in front of the subject's lips, while an experimenter observed the sound level value on a SPL meter (C scale) held next to the microphone. The microphone signal was amplified, recorded, and later low-pass filtered at 4.8 kHz and digitized at 10 kHz. The RespiTrace signal was digitized at 312.5 Hz. Digitization, signal processing, and interactive data extraction were performed with procedures written in the MITSYN languages (Henke, 1989; Perkell *et al.*, 1991) running on a Digital Equipment Corporation engineering workstation. The digitized signals were demultiplexed into two time-aligned signal files.

E. Data extraction

Respiratory patterns and phrase selection. In an attempt to control for the effect of breathing pauses on F_0 and SPL contours, the breath groups in each repetition of the Rainbow Passage were determined from a display of the RespiTrace signal. A breath group is defined as the segment of speech from the beginning of an expiratory limb to the start of the next inspiration. By viewing the RespiTrace signal and listening to the time synchronized acoustic signal, an experimenter marked on a printed copy of the Rainbow Passage the location of the beginning of each breath group in a given speaker's reading. Next, that speaker's first breath group preintervention was compared with the first breath group postintervention and a match was counted if the same one or more phrases of the Rainbow Passage (see Appendix) were in that breath group pre and post. Then the second breath group was compared pre and post for a match, and so on through the passage. Only phrases in breath groups that matched pre- and postintervention were analyzed since the addition or omission of a breath pause after a phrase might be associated with a substantial change in the F_0 and SPL contours of that phrase. The number of phrases that could be matched up in this way ranged, depending on the speaker, from the full 16 in the Rainbow Passage to only half that many. The number of repetitions of each phrase that could be matched up in this way also varied across speakers, with a maximum of 10 and a minimum (required for that phrase's inclusion in the data set) of 4.

Vowel acoustics. Algorithms implemented with a MITSYN command language script were developed to facilitate the acoustic data extraction. A spectrographic display was used to aid in determining vowel boundaries, and a time-aligned amplitude envelope was displayed along with the sound-pressure waveform and F_0 contour. To calculate the SPL of each vowel, the rms of the recorded, digitized signal at the peak amplitude in each syllable nucleus was divided by the rms of the calibration tone and converted to dB. The mean F_0 in each syllable nucleus was determined with an algorithm, supplied with the MITSYN languages, which tracked and displayed individual periods of the voice fundamental. The algorithm, called FPRD, uses heuristic proce-

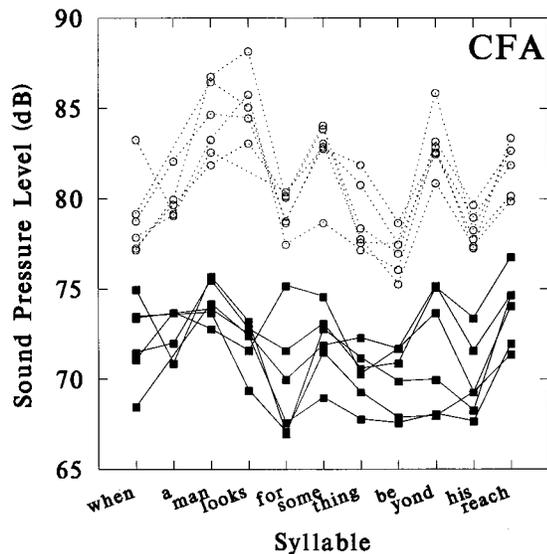


FIG. 1. Sound-pressure level maxima (SPL) for all of the syllable nuclei in the thirteenth phrase of the Rainbow Passage read by subject CFA in two baseline sessions (open circles) and in two recordings made more than a year following the activation of her cochlear implant speech processor (filled squares).

dures to identify individual periods in the sound-pressure waveform (no published reference). The average value of F_0 over the entire vowel duration was retained. Spurious F_0 values due to transition effects, creak, etc., were not included in the calculation of average F_0 for a given vowel.

II. DATA ANALYSIS

To illustrate the procedure followed for data analysis, Fig. 1 plots the SPL maximum of each syllable nucleus in each reading of the thirteenth phrase of the Rainbow Passage by subject CFA in two baseline sessions (open circles) and in the recordings 58 and 85 weeks following the activation of her cochlear implant speech processor (filled squares). (Data points are missing for some individual syllables whose parameter values could not be accurately determined.) The marked reduction in SPL postactivation of the implant user's speech processor hinders comparison of the shapes of contours pre- and postintervention.

Consequently, each of the two sets of contours was averaged and normalized as follows. First, corresponding syllable nuclei in each set of readings (pre- and postactivation) were matched up and their parameter values averaged across the set in arithmetic units (sound pressure in μ bars or F_0 in Hz) to yield an average contour for the set. Next, each value on the average contour was divided by the highest value on that contour and expressed as a percent; the result is shown in Fig. 2. The highest value on the average contour preactivation shown in Fig. 2 occurred during the word **looks**; postactivation, the highest value occurred during the word **man**.

Comparing the average normalized contour in Fig. 2 obtained without auditory feedback (open circles) to that, also shown, obtained with prosthetic hearing (filled squares), it is evident that SPL varies less on the average from syllable to syllable in the condition where auditory feedback was available (filled squares). One way of parametrizing the variation

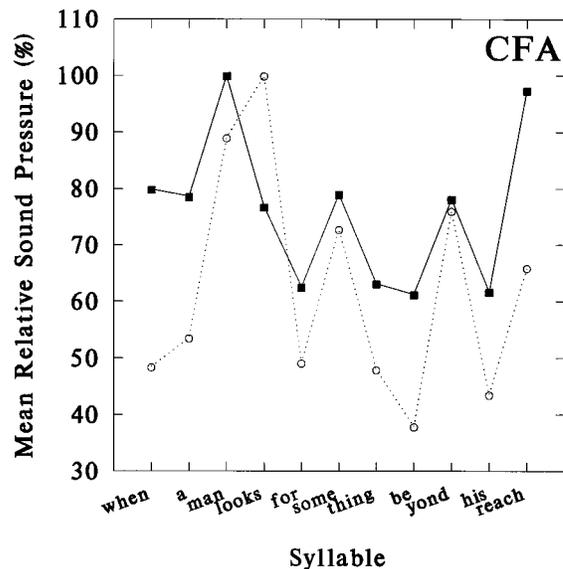


FIG. 2. The SPL contours in Fig. 1 averaged and then normalized. The mean parameter value of each syllable nucleus was divided, for the pre- and postintervention sets of contours separately, by the highest mean parameter value on the contour and the result expressed as a percent. Each point is based on between two and six observations.

in the averaged SPL contour is to subtract the percent-of-maximum value of each syllable from that of the following syllable. These successive differences are positive where the contour is rising and negative where it is falling; the average of their absolute values is the mean successive difference (MSD). The MSD of the preimplant contour in Fig. 2 was 25.3%, that of the postimplant contour 16.3%, a reduction of 9.0% in the average variation of SPL from syllable to syllable following the provision of some auditory feedback. To evaluate the statistical significance of such changes, for each subject, clause, and parameter, corresponding absolute values of successive differences on the pre- and postintervention average contours were paired off. For example, there were 10 such values paired off in clause 13 (Fig. 2; the number of successive differences is one less than the number of syllables). Proceeding likewise for the other ten clauses retained for this speaker (since they were uttered on comparable breath groups pre- and postintervention), there were a total of 73 paired pre- and postintervention measures. The two grand means of the paired measures were entered in Table I, and the reliability of the difference between the means was tested with the t -test for matched pairs and 72 df.

Table I shows the result of comparing pre- and postintervention phrases with respect to MSD in their SPL and F_0 contours for each of the speakers. It presents the value of the t -test for matched pairs of changes in relative syllable sound pressure or F_0 (cols. 4 and 8) and the associated average MSD pooled over all phrases pre- and postimplant separately (cols. 2–3 and 6–7) for the four implant users, or pre- and post-hearing-loss for speaker NFA.

Some indication of the regularity of contours in a hearing subject can be had from the measures obtained with speaker NFA (row 5) before her surgery; although she had a total hearing loss in one ear and a moderate loss in the other, her speech discrimination was excellent, as reported above. However, MSD values in the "Pre" and "Post" columns of

TABLE I. Variation of SPL and F_0 contours. Mean successive differences in normalized SPL and F_0 contours as a function of auditory feedback conditions in four cochlear implant users and an NF2 patient. Preintervention recordings were made prior to activating speech processors in the implant users, and prior to surgery and severe hearing loss in the NF2 patient. The table presents the value of the t -test for matched pairs of phrases and the associated global averages of mean successive differences pre- and postimplant or pre- and post-hearing-loss for the NF2 speaker, NFA. Also shown are the values of MSD for a phrase read by all speakers preimplant (and pre-hearing loss for NFA) that allow between-speaker comparisons (* = $p < 0.05$; ** = $p < 0.01$, two-tailed test).

Subject	Mean successive difference							
	Relative sound pressure (%)				Relative fundamental frequency (%)			
	2	3	4	5	6	7	8	9
	Pre	Post	t PRE vs POST	Common Phrase PRE	Pre	Post	t PRE vs POST	Common Phrase PRE
1 CMD	24.0	24.9	-0.6	34.0	9.1	7.2	3.2**	11.2
2 CFA	26.2	17.9	3.6**	42.8	8.8	6.9	2.7**	9.6
3 CFB	22.0	18.2	2.0*	49.9	5.5	4.4	2.0*	3.8
4 CFC	19.5	19.1	0.2	27.8	4.6	5.0	-0.7	2.4
5 NFA	15.4	21.4	-4.3**	25.8	5.4	6.8	-3.4**	8.4

Table I cannot be used for comparisons among speakers because MSD varies depending on which phrase is considered, and the phrases included in the analysis varied from one speaker to the next, depending on which phrases fell into breath groups that matched from pre- and postintervention in that speaker. In order to make between-subject comparisons of MSD, a phrase in the Rainbow Passage was identified that had been analyzed for all speakers in the preintervention sessions (labeled phrase 9 in the Appendix). The average values of MSD for the “phrase in common” appear in Table I (cols. 5 and 9, for SPL and F_0 contours, respectively). They were obtained in the absence of hearing for the implant users and with hearing for speaker NFA.

III. RESULTS

A. SPL contours

On the phrase in common, the implant user with the highest measure of SPL contour fluctuation preimplant was CFB (MSD=49.9%, row 3, col. 5). This speaker significantly decreased the average variation of her SPL contours (from 22.0% to 18.2%) after extended prosthetic audition ($p < 0.05$). Speaker CFA (common phrase MSD=42.8%) gave a comparable result ($p < 0.01$). Consistent with those results, speaker NFA, prior to her severe hearing reduction, yielded the lowest value of sound pressure contour variation (25.8%) on the phrase read in common by all speakers. She increased the variation of her sound-pressure contours after her auditory capacity was severely reduced ($p < 0.01$). Two implant users, CFC and CMD (rows 4 and 1), did not change SPL contour variation with some auditory feedback supplied, and these were the speakers who varied SPL least preimplant (as indexed by MSD on the phrase in common, col. 5). Implant user CFC had the lowest contour variation before processor activation. Although deaf, her MSD on the phrase in common was quite close to that of speaker NFA prior to her hearing loss. Not surprisingly, then, CFC did not reduce SPL contour variation further with the restoration of auditory feedback. CMD also did not reduce SPL contour fluctuation with implant use.

B. F_0 contours

Table I also shows average MSD for the F_0 contours of the same phrases that were analyzed for SPL variation. All speakers who decreased SPL contour variation with feedback also decreased F_0 contour variation in that condition; however, the converse is not true. To some extent the changes in F_0 pre- and postintervention may reflect the operation of speech production mechanisms that also brought about the SPL changes (Titze, 1991). The product-moment correlations between SPL and F_0 across all the syllable nuclei uttered by each speaker varied from a low of 0.3 ($p < 0.01$) to a high of 0.68 ($p < 0.01$). Lane (1962) found that speakers asked to make magnitude productions of vocal loudness increased F_0 by about 25% for each 10-dB increase in SPL. Applying that estimate to the present study, where speakers on the average had a vocal level 4.34 dB greater without auditory feedback, yields a predicted associated increase in F_0 of 10%; the observed average increase in F_0 was greater, 16%.

Speaker CMD, whose F_0 contour on the phrase in common yielded the highest MSD, reduced F_0 contour variation after more than a year of processor use from MSD=9.1% to 7.2% (see Table I; $p < 0.01$). Speaker CFA had an average MSD in her F_0 contours preimplant of 8.8%. Following more than a year of implant use, her MSD had fallen to 6.9% ($p < 0.01$). Likewise, speaker CFB showed a significant reduction in the variation of her F_0 contours when auditory feedback was supplied ($p < 0.05$), even though her MSD on the phrase in common was low to begin with. Speaker NFA yielded a MSD of 5.4% in her F_0 contours while her hearing was still intact (monaurally); after her auditory capacity was severely reduced, MSD rose to 6.8% ($p < 0.01$). The remaining speaker, CFC, had the lowest value of F_0 contour variation on the phrase in common, and—as was the case with her sound-pressure contours—that measure did not change when auditory feedback was supplied.

It is noteworthy that the values of MSD measured on F_0 contours produced by speakers CFA and CMD in the absence of self-hearing (9.6% and 11.2%, respectively, on the phrase in common) were higher (greater variation) than the

comparable normative value provided by speaker NFA before her binaural hearing loss (col. 9: 8.4%). As we have seen, those speakers significantly reduced inflection of their F_0 contours with the restoration of some self hearing. Speaker CFC, who was the implant user with the lowest value of SPL variation without auditory feedback (col. 5: 27.8%), also had the least F_0 contour variation (col. 9: 2.4%); her value for F_0 variation on the phrase in common was indeed below the value obtained from NFA with auditory feedback (8.4%).

C. Scaled contours

We explored the contributions of three possible components of MSD to the differences observed with and without auditory feedback—namely, jitter, inflection (see Baken, 1987), and average level. (The measures of jitter and inflection, designed to index variation in successive glottal periods, were applied here to changes in the mean SPL or F_0 of successive syllables.) With respect to SPL, three speakers significantly changed MSD and two did not; four of those five outcomes were concordant in the jitter measure (the exception: CFB significantly changed MSD but not jitter) and three out of five were concordant on the measure of inflection. With respect to F_0 , four speakers significantly changed MSD and one did not; all five of those outcomes were concordant in the jitter measure and four out of five in the inflection measure. Thus, speakers who reduced MSD, for example, were not solely inflecting each overall phrase less, nor were they solely reducing fluctuation from one syllable to the next within a phrase.

The subjects spoke with higher SPL and F_0 in the absence of auditory feedback than in its presence (with one exception: CFC did not change average SPL pre- and post-activation). The contributions of average levels of SPL and F_0 to measures of contour variation are reduced in computing MSD when SPL or F_0 values on the average contour (pre- and postintervention) are normalized by the highest value on that contour. To explore another method of reducing the influence of average level, we “scaled up” with-feedback contours to the same average level as their counterpart without-feedback contours: we divided the mean value of each contour obtained with auditory feedback into the mean value of its associated contour obtained without auditory feedback, and then multiplied values on the former contour by this ratio. Finally, MSD was computed for the magnified with-feedback contour and for its no-feedback partner without, however, normalizing each contour by its maximum (since that would nullify the effect of the scale transformation). Scaling the with-feedback contour up toward its partner in this way increases its unnormalized MSD and reduces the difference in MSD between it and the no-feedback contour.

However, wherever the difference in unnormalized MSD was significant without the scaling it remained significant after the scaling: all speakers except CFC yielded significant changes in unnormalized MSD in both SPL and F_0 (CFC did neither) both without the scaling and with it. Hence the differences in measurements of contour variation with

and without auditory feedback cannot be attributed solely to associated differences in average SPL and F_0 .

IV. DISCUSSION

The findings for SPL and F_0 contours of implant users and a NF2 patient summarized in Table I show that speakers without auditory feedback, in the former case, or severely reduced auditory feedback in the latter, read passages with more inflected SPL and F_0 contours than in the presence of auditory feedback. An interpretation of these findings arises from our dual-process theory of the role of auditory feedback in speech production. The theory provides that one of the roles of self-hearing is to monitor transmission conditions, leading the speaker to make changes in speech postures that in turn maintain intelligibility. According to this view, exaggerated SPL and F_0 inflections occur in the absence of auditory feedback since such changes may enhance intelligibility under adverse transmission conditions. This line of reasoning places speaking without auditory feedback in the class of speaking under adverse transmission conditions, and it postulates that increased SPL and F_0 inflection enhance intelligibility under those conditions.

Table II assembles evidence from several studies to support the views that (1) speech prosody in the absence of auditory feedback has much in common with speech prosody under adverse transmission conditions (and under instructions to provide “clear speech”); and (2) that the prosodic parameter values associated with speaking under these three conditions enhance the speaker’s intelligibility.

SPL. Increases in average SPL (row 1) have been found in studies of clear speech, and of speaking in noise (the Lombard effect; see the review in Lane and Tranel, 1971). Lane *et al.* (1970) also found increases in speech SPL under reduced auditory feedback (first reported by Fletcher *et al.*, 1918) and suggest that a common variable controlling the speaker’s increase of sound level in noise and increase of sound level with reduced auditory feedback is the perceived signal-to-noise ratio during speech communication. In postlingually deafened adults (col. 3), SPL was higher than normal prior to implantation, when the speakers received no auditory feedback, and fell following implant use.

F_0 . Table II also cites increases in average F_0 (row 2) reported by one study of clear speech (and one of loud speech—Schulman, 1989; col. 1), by three studies of speech communication in noise (col. 2), and by several studies of the speech of postlingually deafened adults (col. 3), who speak at higher average F_0 without auditory feedback (compared to hearing controls) and at lower average F_0 than formerly when they are provided with cochlear prosthesis (studies labeled “CI”).

Duration. Increases in the duration of words (row 3) have been reported under all three conditions and increases in systematic pausing at syntactic boundaries (row 4) have been found in studies of clear speech. In postlingually deafened adults, Plant (1983) found longer pause durations as well as segment durations, compared to speakers with normal hearing.

F_0 inflection. Increased F_0 inflection (row 6) was found in a study of clear speech. Picheny *et al.* (1986) asked speak-

TABLE II. Increases in parameters of speech prosody reported in the literature under three conditions. (1) Subjects are instructed to speak clearly. (2) Subjects are instructed to speak under adverse transmission conditions, such as masking noise. (3) Postlingually deafened adults are compared with hearing controls or with themselves after receiving a cochlear implant (CI). Also shown (row 7) are studies of the intelligibility of speech produced under these conditions.

1 Parameters that increase	2 Clear speech	3 Adverse transmission conditions	4 Postlingually deafened adults
(1) SPL	Picheny <i>et al.</i> , 1986	Bond <i>et al.</i> , 1989 Clark <i>et al.</i> , 1987 Dreher and O'Neil, 1958 Hanley and Steer, 1949 Lane <i>et al.</i> , 1970 Tartter <i>et al.</i> , 1993 Van Summers <i>et al.</i> , 1988 Webster and Klumpp, 1962	Lane <i>et al.</i> , 1995 (CI, NF2) Leder <i>et al.</i> , 1987b Leder and Spitzer, 1990, 1993 Perkell <i>et al.</i> , 1992 (CI) Svirsky <i>et al.</i> , 1992 (CI)
(2) F_0	Picheny <i>et al.</i> , 1986 Schulman, 1989	Bond <i>et al.</i> , 1989 Clark <i>et al.</i> , 1987 Van Summers <i>et al.</i> , 1988	Binnie <i>et al.</i> , 1982 Lane <i>et al.</i> , 1995 (CI, NF2) Leder and Spitzer, 1993 Leder <i>et al.</i> , 1987 Oster, 1987 Perkell <i>et al.</i> , 1992 (CI) Plant, 1984 Svirsky <i>et al.</i> , 1992 (CI)
(3) Duration (word or segment)	Cutler and Butterfield, 1990, 1991 Lindblom, 1990 Moon and Lindblom, 1989 Picheny <i>et al.</i> , 1986 Schulman, 1989	Clark <i>et al.</i> , 1987 Dreher and O'Neil, 1958 Hanley and Steer, 1949 Tartter <i>et al.</i> , 1993 Van Summers <i>et al.</i> , 1988	Binnie <i>et al.</i> , 1982 Lane and Webster, 1991 Leder <i>et al.</i> , 1987a Leder and Spitzer, 1990, 1993 Perkell <i>et al.</i> , 1992 (CI) Plant, 1983, 1984 Waldstein, 1990
(4) Pausing	Cutler and Butterfield, 1990, 1991 Picheny <i>et al.</i> , 1986		Plant, 1983
(5) SPL inflection			Leder <i>et al.</i> , 1987b Present study
(6) F_0 inflection	Cutler and Butterfield, 1991 Picheny <i>et al.</i> , 1986 Price <i>et al.</i> , 1991	Clark <i>et al.</i> , 1987	Lane and Webster, 1991 Leder <i>et al.</i> , 1986 (CI) Present study
(7) Intelligibility	Bond and Moore, 1994 Chen <i>et al.</i> , 1983 Larkey and Danly, 1983 Picheny <i>et al.</i> , 1985 Tolhurst, 1954, 1957	Dreher and O'Neil, 1958 Peters, 1955 Van Summers <i>et al.</i> , 1988	

ers to read sentences conversationally in one experimental condition and to read them clearly in another condition. They found increases in the range of F_0 (as well as increases in average syllable duration, F_0 , and SPL) when speakers produced clear speech. Similarly, a study of radio news broadcasting style of speech found it to have "more clearly and consistently marked prosodic cues than a non-professional speaking style" (Price *et al.*, 1991, p. 2959); it is included in Table II under clear speech. Clark *et al.* (1987) found increased inflection within words when speaking in noise. Lane and Webster (1991) report this result in postlingually deafened adults and they also found, as mentioned earlier, that pitch prominence was exaggerated in these speakers. Waldstein (1990) found that some deafened adults spoke with greater F_0 range but these subjects as a group could not be distinguished reliably on this measure from their hearing counterparts.

In the present study, we have found greater SPL inflec-

tion and F_0 inflection in the absence of auditory feedback than in its presence. In addition, measures of vowel parameters in word lists read by four of these subjects during the same recording sessions showed higher average SPL and F_0 in the absence of auditory feedback than in its presence (implant users: Lane *et al.*, 1995; NFA: Perkell *et al.*, 1995).

Intelligibility. The last row in Table II lists studies that have measured the change in intelligibility associated with these increases in the parameter values of speech prosody. Clear speech is more intelligible than conversational speech (Chen *et al.*, 1983; Picheny *et al.*, 1985). Bond and Moore (1994) report that talkers who were more intelligible had characteristics similar to those distinguishing deliberately clear speech. When transmission conditions are in fact impaired, speakers do speak more intelligibly. For example, Peters (1955) found that when speakers had their voices filtered electronically and fed back to them their subsequent utterances were more intelligible. The author suggests that

speakers articulated more clearly with filtered auditory feedback because they were trying to compensate for an apparent lack of precision in their speech. Larkey and Danly (1983) found that listener reaction times to inflected sentences were faster than their reaction times to the same sentences presented in a monotone. This result, like that of Picheny *et al.* (1985), who found enhanced intelligibility of recordings with enhanced *F0* inflection, is consistent with our hypothesis that the increased *F0* inflection of our speakers in the absence of auditory feedback is a response to adverse transmission conditions and aimed at enhancing intelligibility.

Prosodic parameters of speech under adverse conditions have been linked in prior studies to clear speech (Lindblom, 1990; Van Summers *et al.*, 1988), emphatic speech (Van Summers *et al.*, 1988), and heightened intelligibility (Lane and Tranel, 1971). We have reviewed some evidence suggesting that prosodic parameters of speech under adverse conditions, in clear speech, and in the speech of postlingually deafened adults may reflect a common underlying process, namely an adaptive response of the speaker to actual or perceived adverse transmission conditions. That response may be aimed at maintaining intelligibility. When speakers think they may not be understood, one of the things they may do is to exaggerate the changes in prosodic parameters that they would normally make. Such a strategy could lead to greater average values of SPL, *F0*, and word durations (Cooper *et al.*, 1985); it might also entail more inflected SPL and *F0* contours. At the same time that some speech synergisms may gradually break down at the phonemic level without auditory validation, yielding a loss in intelligibility (Cowie and Douglas-Cowie, 1983), prosodic changes such as slowing of speech, increased level, and heightened inflection may offset that loss to some degree. It is possible, on the other hand, that any such postural compensation is a fortuitous by-product of the role of self-hearing in regulating prosody and not an adaptive response to apparently degraded transmission conditions. It remains to be determined whether the prosodic changes in postlingual deafness do indeed enhance intelligibility.

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APPENDIX: RAINBOW PASSAGE PHRASES

Division of the Rainbow Passage into 16 phrases, which correspond to the breath groups produced by one or more speakers in this study:

- 1 When the sunlight strikes raindrops in the air,
- 2 they act like a prism and form a rainbow.
- 3 The rainbow is a division of white light
- 4 into many beautiful colors.
- 5 These take the shape of a long round arch,
- 6 with its path high above,
- 7 and its two ends apparently beyond the horizon.
- 8 There is,
- 9 according to legend,
- 10 a boiling pot of gold at one end
- 11 People look,
- 12 but no one even finds it.
- 13 When a man looks for something beyond his reach,
- 14 his friends say
- 15 he is looking for the pot of gold
- 16 at the end of the rainbow.

¹To facilitate subject identification in this paper, subjects are labeled CFA, CFB, and CFC (for the three female) and CMD (for the male) cochlear implant users. In other publications from our laboratory that include findings from these subjects they are identified as, respectively, S09, S15, S23, and S27. Perkell *et al.* (1992) reported on changes in vowel production in four implanted speakers including CFA and CFB. Lane *et al.* (1995) reported on changes in plosive voicing and in postural variables in CFA, CFB, CFC, and CMD. The NF2 patient is designated NFA. The subject descriptions in this study are based on supplemental information and supersede those published in prior studies.

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