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The effect of changes in hearing status on speech sound level and speech breathing: A study conducted with cochlear implant users and NF-2 patients

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According to a dual-process theory of the role of hearing in speech production, hearing helps maintain an internal model used by the speech control mechanism to achieve phonemic goals. It also monitors the acoustic environment and guides relatively rapid adjustments in postural parameters, such as those underlying average speech sound level and rate, in order to achieve suprasegmental goals that are a compromise between intelligibility and economy of effort. In order to obtain evidence bearing on this theory, acoustic and aerodynamic measures were collected from seven adventitiously deaf speakers who received cochlear implants, three speakers who had severe reduction in hearing following surgery for Neurofibromatosis-2, and one hard of hearing speaker. These speakers made recordings of the Rainbow Passage and an English vowel inventory before and after intervention. All but one of the postlingually deaf speakers who received prosthetic hearing reduced speech sound level, SPL. Three of these significantly increased a measure of inferred glottal aperture, $H1-H2$, and their session means for these two parameters were inversely correlated longitudinally. All but one of the speakers terminated respiratory limbs closer to functional residual capacity (FRC) once prosthetic hearing was supplied. Finally, the implant users' average values of air expenditure moved toward normative values with prosthetic hearing. These results are attributed to the mediation of changes in respiratory and glottal posture aimed at reducing speech sound level and economizing effort. © *1998 Acoustical Society of America.* [S0001-4966(98)04211-8]

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BACKGROUND

Research on the consequences of long-term changes in hearing for speech has led us to put forth a dual-process theory of the role of auditory feedback in the production of speech (Perkell *et al.*, 1997). Essentially, that theory proposes that the speaker's hearing serves to ensure his or her intelligibility with minimal expenditure of effort. To achieve this, hearing is used to regulate two speech production processes: maintenance of an internal model and posture setting. In the first process, hearing maintains a robust internal model of the relation between articulation and sound output, which is used by the speech control mechanism to achieve acoustic or perceptual phonemic goals that represent a compromise between intelligibility and economy of effort. [On that compromise, see Lindblom and Engstrand (1989).] In the second process, the speaker's hearing monitors the acoustic environment and guides relatively rapid adjustments in his or her postural parameters, such as those underlying average speech sound level and rate, in order to achieve suprasegmental goals that are also a compromise between intelligibility and economy of effort. Those suprasegmental goals include communicatively appropriate values of speech sound level and rate, and inflection of $F0$ and SPL contours (Lane *et al.*, 1997).

In order to test and refine this theoretical framework, we have been eliciting speech samples, over periods as long as 5 years, from two groups of subjects who have undergone long-term changes in hearing status; namely, deafened adults who have received cochlear prostheses, and patients with bilateral vestibular schwannomas (neurofibromatosis-2 patients, NF-2) who experience severe reduction in hearing capacity after surgery for removal of these ''acoustic neuromas.'' It is well known that a particularly robust effect of short-term changes in hearing status is alteration of speech sound level. The speaker's average sound level increases when the perceptible transmission conditions deteriorate through either an increase in noise level (the Lombard effect) or a decrease in signal level [i.e., the level of the speaker's auditory feedback, Black (1951)]. In complementary fashion, the speaker's average sound level decreases with enhanced signal-to-noise (S/N) ratios: speakers whose auditory feedback is amplified speak more softly (Lane *et al.*, 1970; Fletcher *et al.*, 1918), possibly to economize on effort; Russell *et al.* (1998) have shown that as SPL rises above a comfortable speaking level, speech breathing requires more energy. These short-term changes in speech sound level are consistent with the hypothesis that the speaker infers transmission conditions from perceptible signal and noise parameters and makes postural adjustments in speech breathing

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TABLE I. Subject characteristics and percent correct scores on tests of vowel and consonant identification pre- and/or post-intervention. Speakers with cochlear implants are designated by ''C,'' NF-2 patients who underwent surgery by ''N,'' females by ''F,'' males by ''M'' HMA is a hard-of-hearing male NF-2 patient who received no intervention.

	Cochlear implant users							NF-2 patients			
Speakers	CFA	CFB	CFC	CMA	CMB	CMC	CMD	HMA	NFA	NFB	NMA
Age at onset of change in hearing	18	21	2	0	4	10	0	33	17	17	27
Age at onset of profound loss	33	40	47	31	4	56	36	N/A	27	22	32
Age at intervention	51	50	47	35	46	56	36	N/A	27	22	32
Age at last recording	56	52	49	35	49	59	37	53	31	23	35
Height (cm.)	158	158	170	185	180	185	178	183	168	165	
Weight (kg.)	50	80	59	91	84	84	84	77	67	53	
Smoker	N	Y	N	N	Y	N	N	N	Y	N	N
Vowel ID Pre (% correct)	⋯	⋯	⋯	⋯	⋯	⋯	⋯	40	86	94	23
Vowel ID Post (% correct)	37	80	81	76	50	⋯	65	58	19	75	13
Consonant ID Pre (% correct)	⋯	⋯	⋯	⋯	⋯	⋯	⋯	38	89	94	21
Consonant ID Post (% correct)	48	60	44	49	32	⋯	49	41	22	44	7

and laryngeal parameters that help to maintain adequate levels of intelligibility at minimal expenditure of effort.

In a study of long-term changes in vowel parameters with deafened adults (who later received cochlear prostheses), we found (Perkell *et al.*, 1992) that our speakers read a vowel inventory with anomalously high SPL, averaging 88 dB across the four speakers [about the mean value for ''loud voice'' in normally hearing speakers reported by Holmberg *et al.* (1994); also see Leder *et al.* (1987)]. Those speakers reduced SPL an average of 9 dB (placing them at the Holmberg *et al.* mean for ''normal voice'') once they had received their implants and their speech processors were activated. Thus our speakers seem to have used their hearing to monitor the acoustic environment and to regulate sound level. What adjustments in postural parameters did they make to accomplish this?

In a preliminary report on changes in speech breathing parameters following cochlear prosthesis, with three of the four speakers who served in our vowel study just cited, we found that all subjects, following processor activation, changed their volume of air expended per syllable (LVE/syl) (and their average flow rate) toward normative values during readings of the Rainbow Passage. [Those readings were interleaved in the same recording sessions with the readings of the vowel inventory (Lane *et al.*, 1991)]. We inferred from these findings that our speakers, while deaf, may have adopted unsuitable glottal postures that interacted with respiratory postures, such as those underlying average inspiratory and expiratory levels, in determining air expenditure. We speculated that glottal posture may be difficult to monitor without hearing. Our subsequent study of vowel parameters cited above also reported an indirect index of glottal aperture (the difference in amplitude between the first and second harmonics in the acoustic spectrum, $H1-H2$, during vowel production) along with measures of SPL on the same tokens. The three implant users in the vowel study who reduced speech sound level substantially with processor activation, an average across the speakers of 11.2 dB, increased $H1-H2$ an average of 4.7 dB. Moreover, session means of $H1-H2$ and SPL were correlated longitudinally; the mean product-moment correlation for the three speakers was $r=-0.64$. Thus with some hearing restored, some of the speakers may have achieved SPL reductions, at least in part, with increases in glottal aperture.

To explore further the pattern of changes in speech sound level, speech breathing, and glottal aperture under changes in hearing status, the present study examined changes in six respiratory parameters and two acoustic parameters following interventions that provided or, on the contrary, seriously degraded hearing during speech. Seven of the 11 subjects were deafened adults who received cochlear implants. (Three of these had served for a much shorter period in the preliminary study of speech breathing with cochlear prostheses.) There were also three NF-2 patients whose hearing was severely reduced following surgery for removal of vestibular schwannomas and one NF-2 patient who was hard of hearing and did not undergo any acute change in hearing status.

I. METHOD

A. Subjects

Subject characteristics are given in Table I. Eleven subjects served in this experiment: seven were deaf adults who received cochlear implants (''C'' in the table). Three of these had served in the preliminary study (Lane *et al.*, 1991) for a mean of 11 months after processor activation, but were now followed for an average of 1.8 years longer and now their speech sound levels and inferred glottal apertures were analyzed in conjunction with the respiratory measures. Three subjects were patients with neurofibromatosis-2 (NF-2; designated ''N''), whose auditory nerves were severed during

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tumor removal surgery; two of these (NFA and NFB) received an auditory brainstem implant (ABI, Brackman *et al.*, 1993). Finally, there was one NF-2 patient who was hard of hearing (''H'') and did not undergo any acute change in hearing status. (Females are labeled ''F,'' males ''M.'') Also shown are subjects' scores (percent correct) on an identification test containing ten vowels and 12 consonants. For cochlear implant users, those means are averages over 2–4 test sessions after processor activation. For NF-2 speakers, mean identification scores pre-intervention are based on one or two sessions, post-intervention on 2–4 sessions (except for NFA, 7 sessions). For HMA, the ''pre'' scores shown in the table were obtained during his first visit to the laboratory.

Inspection of the left-hand side of Table I (''Cochlear implant users'') shows that hearing loss began in childhood for four of the seven speakers in this study who received cochlear implants. Six of the seven had adult onset of profound hearing loss (CMB is the exception). The period during which the speaker was profoundly deaf without a cochlear prosthesis varied from a few months to as much as 42 years. After two baseline recording sessions, cochlear implant surgery, and activation of the prosthesis speech processor, recordings were made over periods from 1 to 5 years. The table gives the subjects' age at last recording, as well as their height, weight and smoker status. At the time of their last two post-activation recordings, implant users scored an average of 65% correct on vowel identification and 47% correct on consonant identification.

The right-hand column of Table I (''NF-2 patients'') shows that hearing loss began in adulthood for the hard-of-hearing speaker and NF-2 speakers. At least two baseline recordings were made with the NF-2 patients prior to profound loss, which occurred at the time of surgical intervention. These speakers made additional recordings over a period of 1–4 years. Examining their vowel and consonant identification scores in Table I reveals that NFA and NFB were quite accurate in vowel and consonant identification pre-intervention. Following tumor removal surgery and implantation of an ABI, NFA and NFB were much less accurate. However, NFB using her ABI, attained scores comparable to those obtained by the cochlear implant users. NMA, who did not receive an ABI, had low consonant and vowel identification scores both pre- and post-intervention.

B. Speech elicitation

As the methods for elicitation and measurement of respiratory parameters are detailed in Lane *et al.* (1991), and those for elicitation and measurement of vowel acoustics in Perkell *et al.* (1992), they will be only summarized here. In each recording session, the subject read the first paragraph of the Rainbow Passage (Fairbanks, 1960), consisting of six sentences, three times; about 20 min elapsed between each of the three readings. However, CMA, who had a congenital hearing loss and limited English literacy, read instead ''A Trip to the Zoo'' (Wilson, 1979), with seven sentences. There were at least two pre-intervention baseline recording sessions and between three and nine post-intervention recordings depending on when the subjects entered the research program and their availability. The median number of post-intervention recordings was six. Post-intervention recordings with implant users generally were made at intervals of approximately 0, 4, 12, 24, and 48 weeks, and annually thereafter. Recordings with NF-2 patients and the hard of hearing subject were scheduled at intervals of approximately 20, 40, 80, 120, and 160 weeks. The post-intervention recordings began: (1) when the cochlear implant users began to receive electrical stimulation from their Richards (formerly Symbion) multichannel cochlear implants (Youngblood and Robinson, 1988; Eddington, 1983); (2) six (NFB) or 11 (NFA) weeks after the NF-2 patients with ABIs began to receive electrical stimulation from their implants; (3) 20 weeks following surgery for the NF-2 (NMA) patient who did not receive an ABI, (4) in his initial visit to the laboratory for the hard-of-hearing subject (HMA). The post-intervention recordings were scheduled according to a geometric series of time intervals on the evidence from our earlier studies that speech parameters change more rapidly shortly after intervention and then often stabilize after a period of some months or even years, depending on the subject and parameter.

C. Data extraction and signal processing

In order to obtain volumetric measures of speech breathing, from which inspiratory and expiratory levels, respiratory limb volume, and volume of air expended per syllable were derived, we measured changes in lung volume with an inductive plethysmograph (Respitrace, Ambulatory Monitoring Inc.). To compute the change in lung volume resulting from a respiratory maneuver, the abdominal and rib-cage signals from the two plethysmograph amplifiers are summed (in software, after digitizing) after first weighting by a calibration factor to correct for differences in gain between the two channels. In order to determine the correct proportion of the two signals for a given recording session, we had the subject perform isovolume maneuvers at the beginning and again at the end of each session. In order to arrive at a scale factor for converting the summed volume signal to liters, we had each subject exhale and inhale into a plastic bag that had a calibrated volume of 0.8 liters (a ''Spirobag'').

Amplified signals from the Respitrace and the microphone were recorded and subsequently low-pass filtered and digitized simultaneously at two different rates: 10 kHz for speech and 625 Hz for each of the two respiration signals. The digitized signals were demultiplexed into two separate time-aligned files, and the weighted sum of the respiratory signals was computed and displayed. An operator interactively labeled the beginning and end points of each expiratory limb and counted the number of syllables it included, aided by listening to the synchronized acoustic signal. The labeled events were accessed for calculating respiratory limb duration and limb initiation and termination levels in liters above functional residual capacity (FRC). The ratio of the limb excursion to its syllable count is the average volume per syllable in mL. Articulation rate was estimated as the number of syllables in the limb divided by the limb duration (any nonphonated expiratory segments were included in limb duration). To calculate the average SPL of each respiratory limb, the average rms value of the recorded, digitized sound-

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pressure signal in each respiratory limb was divided by the rms value of a calibration tone and the ratio expressed in dB. This dB value was then added to the metered SPL of the calibration tone to obtain dB (SPL).

Three readings of a vowel inventory, comprising eight English monophthongs spoken in /hVd/ context, were interleaved with those of the Rainbow Passage in each session. During data extraction from these vowels, the amplitudes of the first and second harmonics of each vowel token were determined at vowel midpoint (with a 51.2-ms window), in order to obtain a measure of inferred glottal aperture. The spectral correlates of increased subglottal coupling include an increase of the relative amplitude of the fundamental and reduced amplitudes of the higher frequency harmonics (Klatt and Klatt, 1990). Thus the amplitude difference between the first two harmonics in the acoustic spectrum, $H1-H2$, is an indirect index of inferred glottal aperture. There is evidence that $H1-H2$ is correlated with the open quotient of the glottal waveform and perceived ''breathiness'' of the voice (cf. Ladefoged, 1981; Bickley, 1981; Klatt and Klatt, 1990). $H1-H2$ is corrected for the influence of $F1$, but the measure is invalid when the frequency of the first or second harmonic in the spectrum is within 150 Hz of the first formant (see Perkell *et al.*, 1992).[1] Therefore $H1-H2$ results are limited to the nonhigh vowels.

II. RESULTS: COCHLEAR IMPLANT PATIENTS

Figure 1 presents longitudinal plots of average sound-pressure level (SPL, left panel), and average lung volume expended per syllable (LVE/syl, middle panel) during readings of the Rainbow Passage by each of seven adventitiously deaf adults before and after receiving cochlear implants. Also shown for each speaker are average values of the index of glottal aperture ($H1-H2$, third panel) for the nonhigh vowels measured during readings of a vowel inventory for English. The vertical line in each graph indicates the reference week when each speaker's implant speech processor was activated. An approximate indication of the range of normative values is given by the dotted lines, whose separation equals one standard error around a normative mean. For SPL, dB means and standard errors for males (77.8, 1.2) and females (74, 0.9) were taken from Holmberg *et al.* (1994). For LVE/syl, the respective ml means and standard errors (49, 5; 38, 3) were taken from Hoit *et al.* (1990). Comparable values of LVE/syl were reported for men (48) by Hoit and Hixon (1987) and for women (35) by Hoit *et al.* (1989). For $H1-H2$, the dB values for women (6.6, 0.9) were taken from Holmberg *et al.* (1995); the mean value for men was set 5.7 dB lower (Klatt and Klatt, 1990).

The effects of changes in hearing status on speech sound level, air expenditure, respiratory limb termination levels, and glottal aperture are considered in turn in the following four sections.

A. Reductions in speech sound level

Inspection of Fig. 1, left-hand panel, reveals that two of the deaf speakers (CFC, CMA) read the Rainbow Passage at mean sound levels within the normative range pre-intervention and yielded similar values, close to or within the normative range, in their final two recording sessions with prosthetic hearing. The remaining five speakers, however, had a mean baseline speech sound level above the normative range initially. In each case, an effect of providing prosthetic hearing was to lower speech sound levels, although CFA and CMD showed an intermediate rise and CFB and CMC resumed speaking at higher levels after some sessions. In spite of this considerable fluctuation, the average speech sound levels in these speakers' last two recording sessions, with prosthetic hearing, were reliably lower than in their first two (baseline) sessions, without prosthetic hearing. Table II contrasts average values of speech parameters measured during the two baseline sessions (pre) with those obtained during each subject's last two recording sessions (post). Also shown are the differences in the mean parameter values (pre-post $=\Delta$), and a t test of those differences using matched pairs of sentences in the Rainbow Passage. The change in mean parameter values is shown in boldface when statistically significant ($p<0.05$).

Inspection of the first block of data in Table II (labeled ''1'') shows that six of the seven cochlear implant users significantly reduced SPL, and one significantly increased it. For all seven cochlear implant users taken together, the mean change in SPL, during readings of the Rainbow Passage, pre- to post-processor activation, was a reduction of 2.7 dB [z of combined t values$=19.7$, $p<0.01$; cf. Rosenthal (1991)]. The change in average SPL determined instead from readings of the vowel inventory (Table III, block 1) was somewhat larger: for all implant users pooled, it was a reduction of 4.3 dB ($z=6.5$, $p<0.01$). When reading the Rainbow Passage pre-intervention, all of the deaf speakers but one (CMA) exceeded the speech sound level normative values in Holmberg *et al.* (1994). The highest female SPL for the passage in this study was 80 dB (Table II, block 1). This is the top of the range for a normal female voice (Holmberg *et al.*, 1994). CMB had the highest SPL pre-intervention of all the speakers, 83 dB; the loudest speaker in Holmberg *et al.* (1994) averaged 85 dB. In summary, these postlingually deaf speakers tended to speak in an abnormally loud voice and, when they received prosthetic hearing, characteristically spoke more softly.

B. Changes in volume of air expended per syllable

In general, implant users' changes in air expenditure pre- to post-activation were in the direction of normative values, although the longitudinal functions show considerable fluctuation. Inspection of the middle panel of Fig. 1 reveals that three of the deafened speakers (CMA, CMB, CMC) initially expended air volumes well above the normative range while reading the Rainbow Passage. Baseline measures of LVE/syl pooled over the three speakers averaged 64 ml/syl in the two sessions preceding activation of their implant speech processors (Table II, block 2). After activation, with prosthetic hearing available, these three speakers rapidly reduced air expenditure and then apparently stabilized within the normative range. Their pooled average in the final two sessions was 47 ml/syl.

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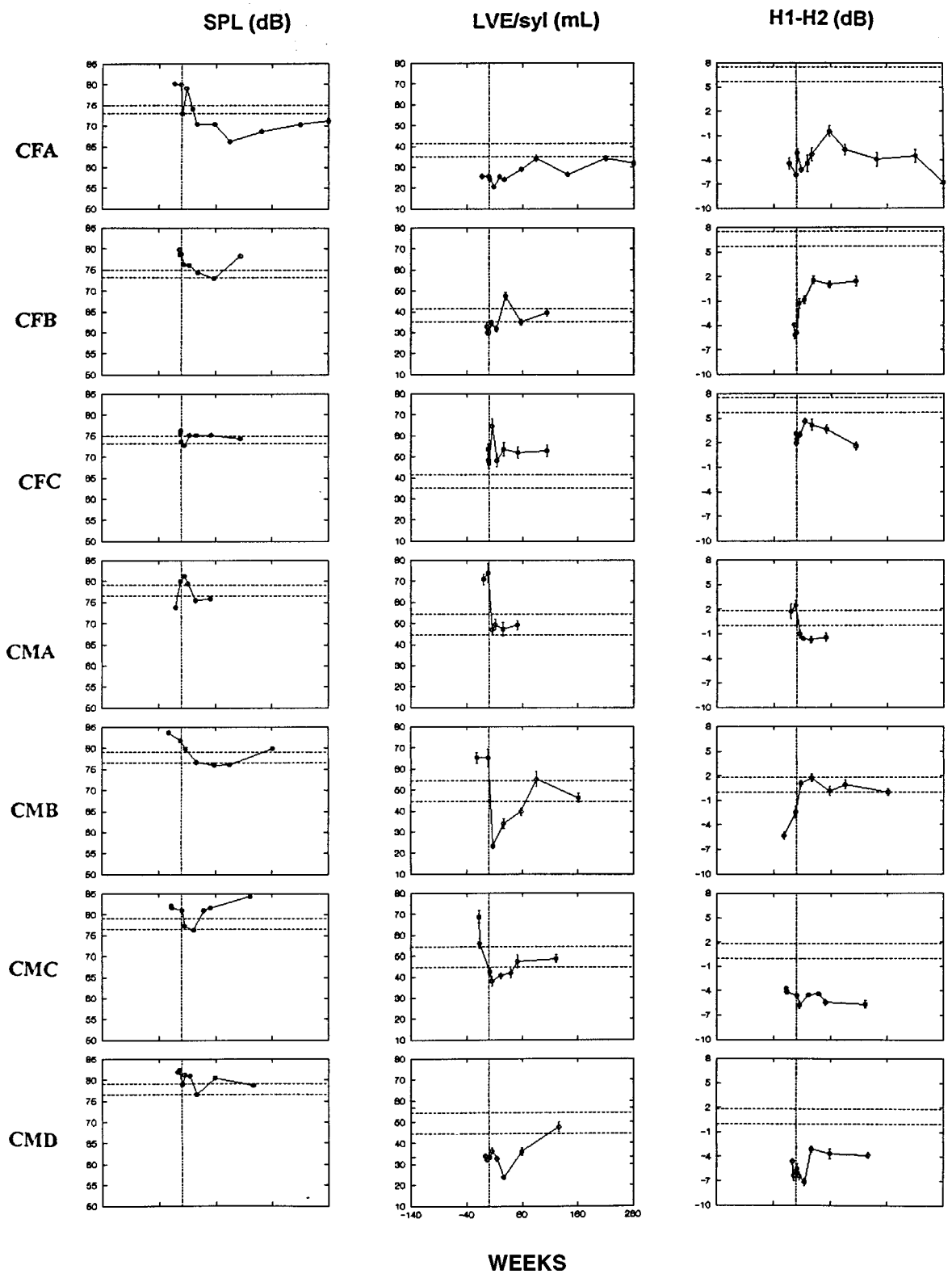

FIG. 1. Longitudinal plots of average sound-pressure level (SPL, left panel), and average lung volume expended per syllable (LVE/syl, middle panel) during readings of the Rainbow Passage by each of seven adventitiously deaf adults before and after receiving cochlear implants. Also shown for each speaker are average values of the index of glottal aperture $H1-H2$, right panel) for the nonhigh vowels measured during readings of a vowel inventory for English. The vertical line in each graph indicates the reference week when each speaker's implant speech processor was activated. An approximate indication of the range of normative values is given by the dotted lines, whose separation equals one standard error around a normative mean.

Three other deafened speakers, in contrast, initially expended air volumes well below the normative range. CFA, CFB, and CMD taken together averaged 29 mL/syl in the baseline sessions. With some self-hearing restored, they gradually (but not monotonically) increased LVE/syl to a pooled mean of 36 ml/syl. Finally, CFC initially expended air volumes a little above the normative range and showed no significant change when comparing baseline and final ses-

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TABLE II. Acoustic and speech breathing parameters during readings of the Rainbow Passage by seven cochlear implant users, three NF-2 patients, and a hard-of-hearing subject pre- and post-intervention. The change in mean parameter value pre-post (Δ) is shown in boldface when statistically significant (*t* test for matched pairs; $p<0.05$). ([1]=Volume *re*: FRC.)

			Cochlear implant users							NF-2 patients			
			CFA	CFB	CFC	CMA	CMB	CMC	CMD	HMA	NFA	NFB	NMA
	Number of sentences	*N*	36	36	36	42	36	36	60	60	54	60	30
1	Speech sound level SPL (dB)	pre	80	79	76	77	83	82	82	63	73	69	65
		post	71	76	75	76	78	83	80	63	72	65	63
		Δ	**9**	**3**	**1**	**1**	**5**	**−1**	**2**	0	1	**4**	**2**
		t	26	5.5	5.1	2.6	9.5	−4.2	9	−1.7	1.8	19.8	11
2	Lung volume per syllable LVE/syl (ml)[1]	pre	25	30	50	71	63	59	32	35	19	25	26
		post	33	36	51	47	48	47	39	33	19	16	37
		Δ	**−8**	**−6**	−0.6	**21**	**15**	**12**	**−7**	**2**	0.4	**9**	**−9.7**
		t	−7.4	−5.5	−0.4	9.2	8.1	5.8	−6	3	0.3	12.4	−8.5
3	Lung volume at limb termination LVT (ml)[1]	pre	2.2	77	−72	−53	−122	−265	−62	−184	−83	−139	−14
		post	8.1	−2.8	−71	−43	−25	−231	−11	−103	33	−9	−132
		Δ	−5.9	**80**	−.5	−11	**−97**	−33	**−51**	**−81**	**−95**	**−130**	**118**
		t	−0.4	3.3	−0.02	−0.2	−2.5	−.8	−2.5	−2.5	−3.9	−6.8	7.2
4	Lung volume at limb initiation LVI (ml)[1]	pre	280	478	321	510	402	450	327	337	326	301	216
		post	410	450	284	349	442	387	476	412	417	322	229
		Δ	**−130**	28	37	**161**	−40	63	**−149**	−75	−67	−21	−15
		t	−3.6	1.1	1.4	2.7	−0.9	1.3	−5.2	−1.9	−1.7	−0.8	−1
5	Lung volume per second LVE/s (ml/s)[1]	pre	94	127	195	183	176	231	136	147	112	142	108
		post	131	162	168	153	149	184	188	141	112	93	135
		Δ	**−37**	**−35**	**27**	**30**	**26**	**48**	**−52**	**6**	−0.6	**49**	**−17**
		t	−11	−7.5	8.7	5.4	5.6	8.3	−11	2.2	−.1	14	−6.1
6	Lung volume of limb LVE (ml)[1]	pre	278	400	393	563	523	714	389	521	409	440	230
		post	402	453	355	392	467	618	487	515	384	331	361
		Δ	**−124**	−52	37	**171**	**167**	**96**	**−98**	6	27	**110**	**−133**
		t	−3.8	−1.6	1.5	2.8	2	2.6	−4.1	0.3	1	5.6	−8
7	Number syllables per limb SYL (N)	pre	11.9	13.9	8.2	8.5	9	12.8	12.7	14.8	21.2	17.7	9.4
		post	12.1	12.9	7.5	9.1	10.4	13.5	13.5	15.5	21.1	21.3	10.5
		Δ	−0.2	1	0.7	−0.6	**−1.4**	−0.7	−0.7	−0.7	0.2	**−3.6**	**−1.6**
		t	−.2	1.1	1.4	−.5	−2.6	−.8	−1.1	−1.8	1.3	−4.4	−2.8
8	Number syllables per second (N/s)	Pre	3.9	4.3	4.1	2.7	2.9	4.1	4.4	4.3	6.2	5.7	4.3
		post	4.1	4.6	3.6	3.4	3.2	4.1	5	4.3	6.1	6.1	3.8
		Δ	−0.2	**−0.3**	**0.5**	**−0.7**	**−0.3**	−0.1	**−0.7**	−0.1	0.1	**−0.4**	**0.7**
		t	−1.6	−3.5	7	−7.9	−7.3	−0.5	−8.2	−0.9	0.4	−3.5	6.6

TABLE III. Mean sound-pressure level and mean index of $H1-H2$ during readings of the vowel inventory by seven cochlear implant users, three NF-2 patients, and a hard of hearing speaker pre- and post-intervention. The change in mean parameter value pre-post (Δ) is shown in boldface when statistically significant (*t* test for matched pairs; $p<0.05$).

			Cochlear implant users							NF-2 patients			
			CFA	CFB	CFC	CMA	CMB	CMC	CMD	HMA	NFA	NFB	NMA
1	Speech sound level SPL (dB)	pre	86	85	80	85	94	86	88	82	79	84	73
		post	76	79	78	83	83	89	87	81	81	80	77
		Δ	**10**	**6**	**3**	**2**	**11**	**−3**	**1**	**1**	**−2**	**4**	**−4**
		t	20	8	6.7	4.9	10	−6.1	4	3.5	−8.3	12.1	−11.9
		N	53	54	50	54	51	53	79	80	80	79	40
2	Inferred glottal aperture $H1-H2$ (dB)	pre	−5.2	−4.6	2.5	2.1	−3.9	−3.9	−5.4	−2.9	−4.9	−4.0	−3.7
		post	−5.2	1.2	2.6	−1.6	0.8	−5.5	−3.7	−2.0	−7.5	−6.6	−2.1
		Δ	−0.4	**−5.9**	−0.4	**4.3**	**−4.9**	**1.4**	**−2**	**−0.9**	**2.5**	**2.6**	**−1.4**
		t	−0.5	−11.6	−1.1	9.3	−6.5	5.1	−4.9	−2.1	6.9	6.5	−2.5
		N	25	32	23	24	14	26	49	49	49	50	25

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sions. Her first session after processor activation, however, showed a rise in air expenditure that was not sustained in later sessions.

We find evidence, then, that prosthetic hearing provided to postlingually deafened adults leads to normalization of their expenditure of air during speech when it was previously abnormal. We did not undertake to collect normative data from hearing speakers; however, several such published studies gave reasonably consistent results. Studying older males, Solomon and Hixon (1993) found an average air expenditure of 47 ml/syl for the Rainbow Passage and Hoit and Hixon (1987) report 48 ml/syl for a different passage. Working with teenagers, Hoit *et al.* (1990) found 49 ml/syl for males and 38 ml/syl for females; these latter means and their standard errors demarcate the ranges in the middle panel of Fig. 1.

C. Changes in limb termination

Five of the seven deaf speakers terminated their respiratory limbs below FRC prior to receiving prosthetic hearing; thus they were encroaching on expiratory reserve. Table II (block 3) shows the average distance from FRC at limb termination pre- versus post-processor activation. Congenitally deaf speakers have also been found to encroach on expiratory reserve (Forner and Hixon, 1977; Itoh and Horii, 1985; Whitehead, 1983). CFA's limb termination levels were very close to FRC while deaf and remained so with prosthetic hearing. All the remaining speakers after receiving prosthetic hearing terminated respiratory limbs closer to FRC. Although those changes, considered individually, are reliable for only three of the six speakers, the combined value of the seven t tests gives a statistically significant result ($z=3.3$, $p<0.01$).

D. Changes in $H1-H2$

Inspection of Fig. 1, right-hand panel, reveals that speakers CFB, CMB, and CMD increased values of $H1-H2$ with prosthetic hearing, moving up toward the normative range (with some fluctuation in CMD's case), indicating that they had adopted a relatively pressed glottal configuration while deaf and assumed a more open posture with stimulation from their implants. Their significant increases in $H1-H2$ (Table III, block 2) were 6, 5, and 2 dB, respectively. Were it not for a drop in $H1-H2$ in their last session, this measure would also have increased significantly for CFA and CFC. Finally, two speakers *reduced* $H1-H2$ after processor activation, indicating that they assumed a more pressed glottal posture: CMA moved from slightly above the normative range to slightly below it, while CMC reduced a low value of $H1-H2$ even further.

For the implant users who increased $H1-H2$ significantly (CFB, CMB, CMD), session means for $H1-H2$ were inversely correlated with those for SPL in readings of the vowel inventory ($r=-0.83$, -0.93, -0.72; $N=8$, 7, 8, respectively; $p<0.05$).

III. RESULTS: HARD-OF-HEARING SPEAKER AND NF-2 PATIENTS

Figure 2 presents longitudinal plots of speech sound level, lung volume expended per syllable, and $H1-H2$ for the hard-of-hearing male speaker (HMA) and the three NF-2 patients who had surgery; the format is comparable to Fig. 1, except for the plots of SPL, where the starting level of the y axis has been lowered to 50 dB to accommodate the lower speaking levels of the NF-2 subjects. The vertical line in each graph indicates the reference week when each NF-2 patient had severe reduction in hearing status and, for NFA and NFB, when each received an auditory brain-stem implant. (For HMA, the vertical line indicates the initial visit to the laboratory.) In the following, we consider first findings for the three parameters for the hard of hearing speaker, then turn to the NF-2 patients and their measures of SPL, LVE/syl, and $H1-H2$.

The hard of hearing subject, HMA, who did not undergo any acute intervention, maintained SPL, LVE/syl, and $H1-H2$ relatively constant over the three years of recording sessions (Fig. 2). Table II (blocks 1 and 2) shows that he did not change speaking level from his first two to his last two sessions, while his LVE/syl dropped 2 ml. This speaker's $H1-H2$ (Table III) increased less than 1 dB. However, since there was little within-session variation of LVE/syl and of $H1-H2$, the small average increases in these parameters were statistically reliable.

If speakers who regain some hearing reduce SPL, as our implant users generally did, then speakers like our NF-2 patients who undergo severe reduction in hearing may be expected to raise SPL. Considering all 11 speakers, the deaf speakers had the highest SPL pre-intervention (80 dB averaged across speakers), whereas the hard of hearing subject and the NF-2 speakers, who had hearing pre-intervention, had the lowest SPL means (68 dB). A comparison of these NF-2 speakers' baseline and final two sessions, showed, contrary to expectation, that mean speech sound levels were *reduced* by 1, 2, and 4 dB; however, these averages obscure considerable variability in speech sound level from session to session. All three speakers showed an initial rise in speech sound level in the session immediately after intervention, as expected (Fig. 2). NFA's average SPL then fell for several sessions, and finally rose again, leaving a comparison of the first and last two sessions with no significant change. NMA's speech sound level also rose initially but then returned to near baseline values. NFB's rise in level post-intervention was attributable to a peculiarly low value just before intervention; final values average 4 dB below baseline. It is difficult to interpret the findings for NFA and NFB in relation to the control of speech sound level by hearing because there is no independent comparison of their perception of the relative loudness of speech before and after receiving their ABIs. NFA achieved stress perception scores as high as 90% correct with her ABI, NFB 80% correct (MTS test; Erber and Alencewicz, 1976). Thus it is possible that these speakers, because of their ABIs, actually perceived their speech to be louder than pre-intervention. NMA, who had a severe reduction in hearing capacity and did not receive an ABI, decreased SPL in the Rainbow Passage by 2 dB (Table II),

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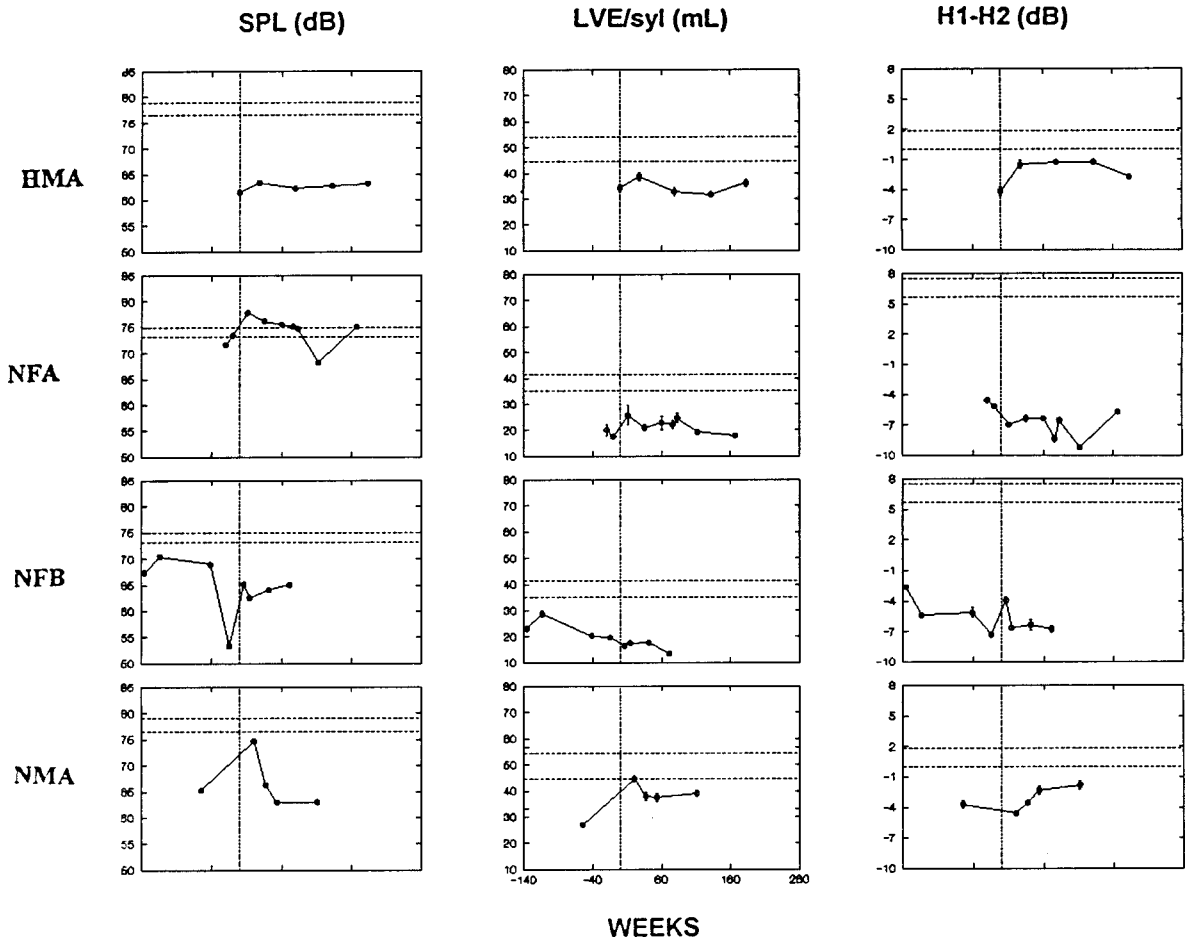

FIG. 2. Longitudinal plots of SPL, LVE/syl, and $H1-H2$ for the hard of hearing male and NF-2 patients; the format is comparable to Fig. 1, except for the plots of SPL, where the starting level of the y axis has been lowered to 50 dB to accommodate the lower speaking levels of the NF-2 subjects. The vertical line in each graph indicates the reference week when each NF-2 patient had severe reduction in hearing status and, for NFA and NFB, received an auditory brain-stem implant.

contrary to expectation, but he increased it by 4 dB when reading the vowel inventory (Table III).

Our finding that six of the seven implant users approached normative values of air expenditure during reading once they received some prosthetic hearing leads us to expect that speakers who lose their hearing will deviate from normative values and expend either too little or too much air. Figure 2 shows that all three NF-2 patients had anomalously low LVE/syl while reading prior to their surgery. Following surgery, one speaker maintained low LVE/syl (NFA), one lowered it further (NFB), and one moved toward normative values (NMA). NFA's continued low air expenditure was not the result of particularly shallow speech breathing (Table II, block 4) and may have been due to a pressed glottal posture; the index of her inferred glottal aperture averaged −7.5 dB (Table III, block 2); the female norm reported by Holmberg *et al.* (1995) was +6.6 dB. NFB's further reduction of LVE/syl post-intervention may have been the result of her adopting a more pressed voice (the index of inferred glottal aperture fell to −6.6 dB) and making less incursions below FRC (Table II, block 3). NMA, following severe hearing loss, terminated respiratory limbs well below FRC; this substantially increased the size of his respiratory limbs and hence LVE/syl (block 2). Thus NMA's air expenditure moved towards normative values following hearing loss but it did so because of an anomalous mechanism, he now encroached on expiratory reserve air. Three cochlear implant users also increased LVE/syl but the mechanism they employed was quite different from NMA's use of reserve air: with hearing provided, the CI users who expended more air did so by taking deeper breaths (CFA, CMD) or by extending limbs toward FRC (CFB).

Our finding that five of the seven deaf speakers encroached on expiratory reserve when reading (before receiving prosthetic hearing) leads us to expect that, in general, speakers who become deaf will make greater incursions into expiratory reserve, as did NMA. However, NFA and NFB reduced incursions into reserve air post-intervention (Table II, block 3). This may be related to their receiving ABIs since NMA, who did not receive one, did significantly increase incursions into expiratory reserve after severe hearing loss, as expected. It is unclear, however, what information the ABIs provided that made the difference.

Table III (block 2) shows that the two ABI recipients, NFA and NFB, decreased $H1-H2$. We infer that they assumed more pressed glottal posture. (Although comparison of baseline and final sessions yielded a significant reduction, the time courses for both speakers showed substantial fluc-

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TABLE IV. Patterns of change in acoustic and aerodynamic measures following change in hearing status. (A check mark indicates the pattern described at the left was found, while ''No'' indicates a result contrary to the pattern. ns=no significant change or correlation. An asterisk indicates a result that, taken individually, followed the pattern but was not reliable; however, combining the probabilities of a type I error across speakers showed that pattern to be statistically significant.)

		Cochlear implant users							NF-2 patients			
	Speakers:	CFA	CFB	CFC	CMA	CMB	CMC	CMD	HMA	NFA	NFB	NMA
A	Decreased speech sound level	√	√	√	√	√	No	√	ns	ns	√	√
B	Approached normative air expenditure	√	√	ns	√	√	√	√	ns	ns	No	√
C	Limb termination approached FRC	ns	√	√*	√*	√	√*	√	ns	√	√	No
D	Increased inferred glottal aperture	√*	√	ns	No	√	No	√	√	No	No	√

tuation; cf. Fig. 2.) It may be that their very low rates of air expenditure post-intervention reflected in part a substantially reduced subglottal pressure, and their pressed glottal postures were required to sustain phonation. NMA had much higher rates of air expenditure post-intervention than NFA and NFB and did not decrease his index of inferred glottal aperture, indeed, he increased $H1-H2$ by 1.4 dB (Table III, block 2).

All three subjects who were able to hear speech to some extent before *and* after intervention, NFA and NFB because of their ABIs, HMA because he was hard of hearing, read at the highest rates in this study (Table II, block 8: averaging across speakers, their pre-intervention speaking rate was 5.4 syl/s, post-intervention, 5.5 syl/s). They also took the fewest breath pauses, and thus had the largest number of syllables per limb (Table II, block 7): an average of 17.9 and 19.3 pre- and post-intervention, respectively. Perhaps influenced by their ability to hear speech, these speakers frequently uttered an entire sentence, or more than one sentence, in each breath group, which led them to draw on reserve air and may have contributed to their low lung volumes expended per syllable. Finally, the patients who received ABIs reduced these incursions into expiratory reserve significantly from baseline to the final two sessions. High rate, infrequent breath pauses, low levels of air expenditure, and low SPL; this pattern of results is consistent with a strategy of speaking fluently and intelligibly while minimizing energy expenditure.

IV. GENERAL DISCUSSION

In spite of considerable fluctuation in session means for speech sound level, air expenditure, and inferred glottal aperture, a generally coherent picture emerges from these results. Of the 11 speakers in this study, the seven who were deaf pre-intervention had the highest SPL pre-intervention and six of the seven lowered their SPL when the processors of their implants were activated.

Consistent with these results, the dual-process theory leads to the prediction that speakers will increase their sound level if they undergo severe hearing reduction since, following hearing loss, transmission conditions appear to the speaker to be degraded, the perceived signal level goes to zero while other indices of a communication breakdown arise from listener behaviors. In complementary fashion, when an adventitiously deaf speaker receives prosthetic hearing, apparent signal level increases and that speaker will speak more softly when compatible with the current communicative demands.

With some hearing restored, each of the speakers came closer, on the average, to terminating respiratory limbs near FRC (except for CFA who terminated limbs close to FRC while deaf and continued to do so with prosthesis). This result is also consistent with the dual-process theory: under changing conditions for speech transmission, the speaker seeks to ensure adequate speech sound level for intelligibility while minimizing effort. Although we do not measure effort directly, we hypothesize that more effort is expended when the speaker sustains phonation below FRC than above. In order to sustain subglottal pressure below FRC, the speaker must work against the recoil pressures of the respiratory system which are inspiratory. Russell *et al.* (1998) conclude from their study of ventilatory responses during passage reading that ''the respiratory system is controlled during speech to minimize energy expenditure'' (p. 246) and Forner and Hixon (1977) have suggested that when their congenitally deaf speakers were encroaching on reserve air, they were using excessive muscle pressure.

Table IV shows patterns of change in acoustic and aerodynamic measures of the speech of implant users and NF-2

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patients following intervention. (A check mark indicates the pattern described at the left was found, while ''No'' indicates a result contrary to the pattern. ns=*no* significant change or correlation; an asterisk indicates a result that, taken individually, followed the pattern but was not reliable; however, combining the probabilities of a type I error across speakers showed that pattern to be statistically significant.) Six of the seven implant users decreased speech sound level (row A). The same number modified their air expenditure in the direction of normative values (B). Six of the speakers also terminated respiratory limbs closer to FRC (C). Four of the speakers increased $H1-H2$ (D).

The pattern of individual results for the implant users (Table IV) indicates that, in several cases, SPL reductions were most likely achieved by increasing glottal aperture, thereby increasing coupling to the trachea, which acts like an antiresonance in the vocal-tract transfer function and attenuates the first formant of low vowels (Perkell *et al.*, 1992). This idea is supported by the observation reported above that three of the four implant users with the largest SPL reductions post-intervention also showed increased $H1-H2$ and reliable longitudinal correlations of SPL and $H1-H2$; the fourth speaker fits this pattern except for her most recent recording. All the speakers who received prosthetic hearing, both cochlear prostheses and ABIs, terminated respiratory limbs closer to FRC post-intervention, by hypothesis to economize on effort. Conversely, the NF-2 patient who had severe hearing loss and did not receive an ABI subsequently read with substantial incursions into expiratory reserve capacity.

Finally, inference from our findings suggests that the implant users' increases and decreases in air expenditure toward normative values with prosthetic hearing were not directly regulated by hearing but were rather a by-product of changes in respiratory and glottal posture made to achieve reductions in SPL (which were directly regulated by hearing) and reductions in the effort expended to initiate expiratory limbs and sustain them with reserve air.

The findings concerning changes in rate of speaking with changes in hearing status are also reasonably consistent with the dual process theory. All of the seven adults with adventitious deafness read the Rainbow Passage initially at articulation rates below the normative range found with 14 hearing males reading the Rainbow Passage (Solomon and Hixon, 1993): 4.9 syl/s +/− 0.3, see Table II, block 8. [Lane and Grosjean (1973) reported a similar average articulation rate of 4.8 syl/s for 12 hearing speakers reading a different passage.] Slower reading rates are associated with ''clear speech'' [e.g., Picheny *et al.* (1986)] and with greater intelligibility [e.g., Picheny *et al.* (1985)]. When prosthetic hearing was provided to those speakers, five of the seven implant users increased articulation rate (four of them reliably), one did not change, and one decreased. (The prosthesis effect may be confounded with a practice effect, although the hard of hearing subject who received no intervention did not alter speaking rate significantly over five sessions spanning more than three years.) The slower articulation rates associated with deafness and with clear speech may come with a greater cost in effort. Following this line of reasoning, speakers chose to reduce that effort once transmission conditions appear to have improved. Thus like the findings for speaking level, those for articulation rate support the view that speakers use self-hearing to monitor transmission conditions and regulate speech parameters in order to achieve a compromise between intelligibility and effort.

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[1]The correction for the influence of $F1$ in dB subtracted from the first and second harmonic amplitudes was $20*\log_{10}(1/(1-(f_{H1}/f_{F1})^2))$ (where f_{H1} is the frequency of the harmonic and f_{F1} is the frequency of the first formant).

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