

Effects of bite blocks and hearing status on vowel production^{a)}

Harlan Lane^{b)}

Department of Psychology, Northeastern University, Boston, Massachusetts 02116 and Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139

Margaret Denny

Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139

Frank H. Guenther

Department of Cognitive and Neural Systems, Boston University, Boston, Massachusetts 02215 and Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139

Melanie L. Matthies

Department of Health Sciences, Boston University, Boston, Massachusetts 02215 and Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139

Lucie Menard

Université de Québec à Montréal, Québec, Canada and Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139

Joseph S. Perkell

Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139; Department of Cognitive and Neural Systems, Boston University, Boston, Massachusetts 02215; and Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Ellen Stockmann

Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139

Mark Tiede

Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139 and Haskins Laboratories, New Haven, Connecticut 06511

Jennell Vick

Department of Speech and Hearing Sciences, University of Washington, Seattle, Washington 98105 and Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139

Majid Zandipour

Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Room 36-511, 50 Vassar Street, Cambridge, Massachusetts 02139 and Department of Cognitive and Neural Systems, Boston University, Boston, Massachusetts 02215

(Received 6 December 2004; revised 28 June 2005; accepted 28 June 2005)

^{a)}The order of authors after the first is alphabetical.

^{b)}Electronic mail: lane@neu.edu

This study explores the effects of hearing status and bite blocks on vowel production. Normal-hearing controls and postlingually deaf adults read elicitation lists of /hVd/ syllables with and without bite blocks and auditory feedback. Deaf participants' auditory feedback was provided by a cochlear prosthesis and interrupted by switching off their implant microphones. Recording sessions were held before prosthesis was provided and one month and one year after. Long-term absence of auditory feedback was associated with heightened dispersion of vowel tokens, which was inflated further by inserting bite blocks. The restoration of some hearing with prosthesis reduced dispersion. Deaf speakers' vowel spaces were reduced in size compared to controls. Insertion of bite blocks reduced them further because of the speakers' incomplete compensation. A year of prosthesis use increased vowel contrast with feedback during elicitation. These findings support the inference that models of speech production must assign a role to auditory feedback in error-based correction of feedforward commands for subsequent articulatory gestures. © 2005 Acoustical Society of America. [DOI: 10.1121/1.2001527]

PACS number(s): 43.66.Ts, 43.70.Bk, 43.70.Dn, 43.70.Fq [AL]

Pages: 1636–1646

I. INTRODUCTION

As part of a broader inquiry into speech production, our laboratory has had a longstanding interest in determining the role of auditory feedback in that performance (Perkell *et al.*, 1992; Guenther and Perkell, 2004). To that end, our research has investigated speech production in late-deafened adults who have had no auditory feedback for many years. When those adults have some hearing restored with cochlear implants, we measure acoustic parameters of their speech again, as well as their phoneme perception. In some studies such as the present one, we also switch off implant microphones in order to block auditory feedback for short periods of time. Finally, we make measures of speech perception and production in participants with normal hearing, in order to have some normative benchmarks.

One method of investigating the role of auditory feedback in speakers with normal hearing that has attracted wide interest is to measure speech parameters while the subject clenches a bite block between the teeth and produces a set of utterances. It turns out that such speakers' vowel formants are only slightly altered from their unperturbed state. Moreover, evidence for this compensation can be found in measures of the first glottal pulse, indicating that most of the needed reorganization was not accomplished with the aid of closed loop auditory feedback (Lindblom and Sundberg, 1971; Lindblom *et al.*, 1978; Lubker, 1979; Flege *et al.*, 1988; Baum *et al.*, 1996). McFarland and Baum (1995) found that compensation to bite blocks was neither immediate nor complete and, at least for vowels, compensation strategies may develop over time. Flege *et al.* (1988) measured linguapalatal contact patterns in /s/ and /t/ and found that ten minutes' conversation with bite block led to normal acoustic parameter values; they suggest that sensory feedback may have provided error based correction of articulatory gestures. Hoole (1987) gave bite blocks to a German-speaking patient who had suffered loss of oral sensation due to head trauma. Neutralization of vowels was particularly marked in the bite block plus masking condition and there was no evidence of learning. Hoole concludes that afferent information is required to "establish a frame of reference for motor commands" (p. 19).

The combined interventions of bite block and changes in hearing status present an opportunity to test several hypotheses concerning dispersion and vowel contrast. The present experiment employs postlingually deaf adults to test these hypotheses since prelingually deaf participants may not have mastered the phonemic system or the motor commands and feedback mechanisms required for speech. Remarkably, there appears to be only a single published study in which bite blocks were used with postlingually deaf adults (Tye *et al.*, 1983).

Should we expect that late-deafened adults, asked to speak while clenching a bite block between their teeth, will compensate as accurately as their normal-hearing counterparts? On the one hand, yes, for late-deafened adults had the normal opportunity to master speech production and to monitor their own speech aurally (as well as somesthetically). If speakers with normal hearing do not require closed-loop auditory feedback for accurate compensation, then late-deafened adults who have little or no auditory feedback may have no disadvantage in this regard. On the other hand, no, for late deafened adults have been for some time without sufficiently acute hearing to "update" their model of the relations between the configuration of the vocal tract and its auditory consequences. Speakers with normal hearing are able to update their model when there is drift, when oral morphology has changed, or indeed, when speaking with something in their mouths (Jones and Munhall, 2003).

A. Theoretical background

In thinking about such issues and in formulating experimental hypotheses, our theoretical framework has been guided by the DIVA model of speech motor planning (Guenther and Perkell, 2004). When controlling a model of the vocal tract, DIVA accounts qualitatively for a wide range of observations on speech production, including speech sound acquisition, articulatory variability, motor equivalence, coarticulation and rate effects (Guenther, 1994; Guenther, 1995; Guenther *et al.*, 1998).

Figure 1 presents a schematic of how feedforward and feedback mechanisms are hypothesized to interact in speech motor planning according to our framework. Representations of speech sounds, syllables, and words are stored in long-

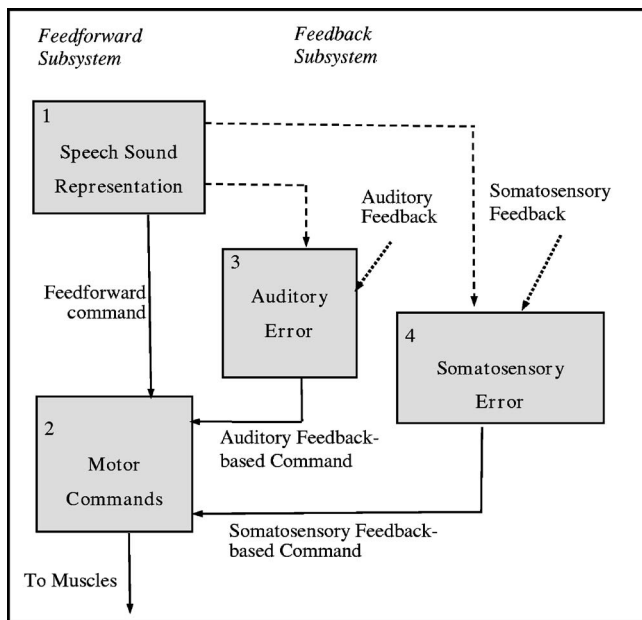


FIG. 1. Schematic diagram of the functionality of the DIVA model. Cells in premotor, motor, and sensory cortical areas are indicated by boxes. Dashed lines: projections from premotor to sensory cortex that encode expected sensory consequences. Dotted lines: projections from sensory periphery to sensory cortex. Solid lines: projections that encode motor commands.

term memory (box 1). (These representations are acquired as the developing child generates vocal-tract movements and begins to form associations among the motor commands, the resulting sounds, and their linguistic significance.) The production of an utterance consisting of a sequence of sounds involves the activation of two sets of projections from the stored representations: (1) projections in the feedback subsystem of *expected auditory consequences* of the movements to be produced. These projections, called *auditory goals*, correspond to regions in multidimensional auditory-temporal space. (2) *Feedforward* projections that result in motor commands to the articulators. As the movements evolve and sound is generated, auditory feedback about the movements' actual consequences is compared with the auditory goals, and if there is a mismatch, an auditory error signal (box 3 in Fig. 1) arises and leads to auditory feedback-based corrective motor commands. These corrective motor commands are also used to help refine feedforward commands for subsequent movement attempts. Eventually, as feedforward commands become well tuned, the control becomes almost entirely feedforward.¹ As the child is learning to produce speech sounds, patterns of somatosensory feedback are also generated. These patterns become incorporated into somatosensory goals, which are used in comparison with somatosensory feedback for error correction as part of the feedback control subsystem.

B. Vowel dispersion hypotheses

Hypothesis (1): A bite block will increase *deaf speakers'* dispersion of vowel tokens around their target means in the formant-1 \times formant-2 plane.

When late-deafened adults have had little or no hearing available for a long time, the bite block is expected to disrupt

their speech production extensively since such speakers' feedforward commands (box 1 to box 2, Fig. 1) were established many years earlier. With a bite block inserted, that mapping is likely to be invalid in some degree but speakers have no way without being able to discriminate the changes in their speech to update such mappings in order to achieve the desired auditory phonemic goals.

Hypothesis (2): The effects of the bite block on *implant users'* vowel dispersion will be less after a year of prosthesis use compared to a month of such use.

When the deaf participant has been using a cochlear implant for an extended period, he or she is better able to retune the articulatory-to-acoustic mappings that will be used to compensate for the subsequent introduction of the bite block.

Hypothesis (3): Speakers with *normal hearing* will respond to the introduction of a bite block with lesser increases in dispersion of vowel tokens than implant users.

Speakers with normal hearing are expected to have more accurate articulatory to auditory mappings in the first place since they have had the possibility of updating those mappings continually. Further, their auditory error signal may be more accurate since their hearing does not have the reduced bandwidth and distortion arising from the use of a cochlear implant. Consequently, when movement trajectories for achieving a given vowel target are modified after a bite block has been introduced, the range of those trajectories is more constrained in normal-hearing speakers.

Hypothesis (4): *Implant users and speakers with normal hearing, speaking with bite blocks inserted, will increase vowel token dispersion during short-term interruptions in auditory feedback.*

In the presence of the bite block perturbation, movement trajectories are more consistent across trials when an auditory error signal is available to correct subsequent feedforward commands; when that signal is interrupted, dispersion increases.

C. Vowel separation hypotheses

The preceding hypotheses regarding the effects of bite block and hearing status on dispersion are linked to hypotheses concerning their effects on vowel contrasts, for high dispersion leads to low contrast (and conversely) according to the theoretical framework we have sketched. To see the reason for this connection, consider Fig. 2, a schematic of two trajectories that pass through a sequence of goal regions, C1, V1, C2, and V2. It will be seen that the larger goal regions (closed squares) give rise to reduced vowel contrast (closed double-headed arrow). That is because the trajectory, guided by least effort (Lindblom, 1980; 1990), passes through the most proximal parts of the goal regions, thereby reducing its travel and hence vowel separation. Therefore:

Hypotheses (5): Insertion of a *bite block* will decrease vowel separation, (6) less so for hearing speakers than for implant users; (7) vowel separation will increase after extended *implant use*, and (8) it will diminish with *short-term interruptions* of auditory feedback.

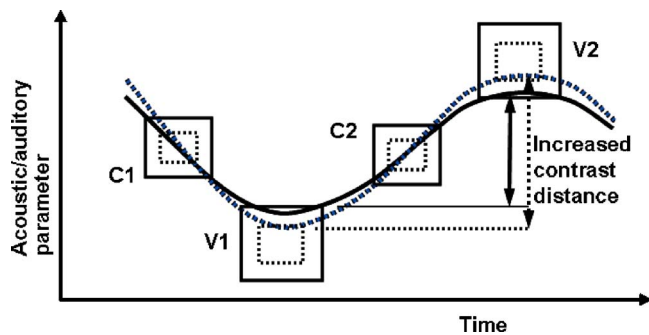


FIG. 2. According to the DIVA model, during speech production an auditory trajectory is planned to pass through the sequence of auditory goals that correspond to the input phoneme string. When the dispersion of the goal region is reduced (dotted squares), the contrast distance between the goals increases (dotted double-headed arrow).

II. METHOD

A. Participants

The experimental group was comprised of six male and two female postlingually deaf, adult, paid volunteers, speakers of Standard American English. Table I shows that the group was heterogeneous in several respects, as is characteristic of this population. Age at onset of hearing loss ranged from birth to 60 years; age at onset of profound loss from 26 to 72. Duration of profound loss varied from less than a year to ten years; the average age of receiving an implant ranged from 28 to 78. Subjects' consonant recognition scores measured before activation of their implants ranged from 21% to 49% correct, and their vowel recognition scores from 25% to 64%. For a description of the phoneme recognition test, see Lane *et al.* (2005) The implant was either the Clarion (Advanced Bionics), cf. Wilson *et al.* (1995); or the Nucleus 24, (Cochlear Corp.), cf. Blamey *et al.* (1987) and McKay and McDermott (1993).

A control group was comprised initially of four male and six female participants, speakers of Standard American English, who reported no speech or hearing anomalies. A screening test was administered to speakers in this group over age 40, in order to determine approximate thresholds at 0.5, 1, 2, and 4 kHz. After a practice tone at 50 dB HL, sound pressure was increased in 5 dB increments from 0 to

25 dB HL or until the subject reported hearing a tone. The series was presented twice at each of the four frequencies to each ear. Subjects who failed to report hearing the tone in any of the 16 series were excluded; this resulted in excluding two male participants, leaving eight subjects in the group. Cochlear implant users participated in four recording sessions, two pre-implant, one approximately a month after activation of their implant speech processors, the other approximately a year after activation. The normal-hearing controls served only once.

B. Procedure

The elicitation set consisted of five /hVd/ words. Before each utterance in a bite block condition, a bite block made of plastic (the kind used in football mouth guards) was inserted between the participant's upper and lower left first bicuspid. The thickness of the bite blocks varied inversely with typical jaw opening for each vowel, as follows: *heed* 2.5 cm; *hid* 2.0 cm, *head* 1.5 cm, *had* 1.0 cm, *hot* 0.5 cm. These sizes were chosen to significantly disrupt the vertical displacement of the jaw relative to its normal position (informally observed) for the particular vowel, e.g., a large bite block was used to force an unnaturally large opening during the high vowel in "heed," whereas a small bite block was used to force an unnaturally small opening for the low vowel in "hot."

Implant users were tested in two sessions prior to activation of the speech processors of their cochlear implants, at one month postactivation and at one year postactivation. For the control group, only a single time sample was recorded. For all subjects, twenty repetitions of each of the five hVd words, uttered in isolation with emphasis on the vowel, were elicited in random order in each of four experimental conditions—the four possible combinations of auditory feedback available or not and bite block inserted or not: (1) No bite block, auditory feedback; (2) No bite block, no feedback; (3) Bite block, no feedback; (4) Bite block, auditory feedback. Since a vowel-specific bite block was inserted for each trial and the vowel order was randomized, the bite block was changed between trials in the bite block conditions. The four experimental conditions were always presented in the order just given with one exception: Feedback was not varied with the deaf participants in the recording

TABLE I. Characteristics of participants with cochlear implants.

Speakers	FI	FJ	MJ	MK	ML	MM	MO	MP
Consonant perception (% correct)	26	25	21	24	21	32	49	21
Vowel perception (% correct)	29	26	35	25	64	32	51	27
Etiology	Autoimmune response	Infection	Hereditary	Unknown	Infection	Noise (WWII)	Blood clot	Hereditary
Age at onset of change in hearing	19	5	Early 30s	18	10	20	60	Birth
Age at onset of profound loss	54	45	43	28	48	72	67	26
Age at cochlear implantation	56	46	49	28	48	78	72	36
Hearing aid used before implantation	None	None	Left	None	None	Both	Left	Both
Implant	Nucleus-24	Clarion	Clarion	Clarion	Nucleus-24	Clarion	Clarion	Clarion

session prior to activation of their implants. They received only the no-bite-block followed by the bite-block conditions. To simulate to a limited degree the implant users' lack of auditory feedback in the processor-off condition, the speakers with normal hearing had their auditory feedback masked by speech-shaped noise presented at 95 dB (SPL).

C. Equipment

Speakers were seated in a sound-attenuating room in a comfortable office chair. A head-mounted electret microphone (Audio-Technica, model AT803B) was placed at a fixed distance of 20 cm from the speaker's lips. Elicitation utterances were presented on a monitor. For the feedback-off condition, participants with normal hearing wore calibrated TDH-39 headphones with ear cushions. The headphones were supplied with noise from a custom-built device (Technical Collaborative, Lexington, MA). The noise was approximately speech-shaped, with a spectral envelope that rolls off at 6 dB per octave. Participants with cochlear prostheses used the normal settings of their speech processors for the feedback-on conditions. For the feedback off conditions, the input to their processors was turned off.

For calibration of sound pressure level, a sound generator (electrolarynx) was placed in front of the speaker's lips while an experimenter observed the sound pressure level on a sound level meter (C scale) placed next to the microphone. The calibration signal and participants' speech were low-pass filtered at 7.2 kHz and digitized in real-time with a 16 kHz sampling rate.

D. Data extraction

The start and end of each token (/hVd/) were labeled automatically based on smoothed rms thresholding exceeding 20% of the peak value for the utterance. The first and second formants were extracted algorithmically from an LPC spectrum around mid-vowel (half the interval from onset to offset) using a 40 ms analysis window for F0 and a 25 ms window for the formants. The algorithm displayed, for each vowel token, (a) LPC-derived formant estimates computed initially at mid-vowel; (b) a broadband spectrogram on which was superimposed the formant trajectories that were detected; and (c) the spectral cross section at the measurement time. In a preliminary pass through the data, the experimenter set the formant bandwidth and LPC filter order to optimize formant identification in each subject's vowel tokens. In the data collection pass, if three formants were detected unambiguously in the regions expected for that vowel target, the experimenter accepted that token with those values as complete and moved on to the next. If the algorithm did not succeed in detecting a formant, the experimenter shifted the time of spectral analysis between one and three pitch periods.

To measure dispersion, we determined for each utterance of a phoneme the Euclidean distance of that single token in the F1 × F2 plane from the average position of all the tokens of that phoneme. Then, those deviations were converted to logarithms (to render the distributions more normal) and averaged across repetitions and subjects to obtain

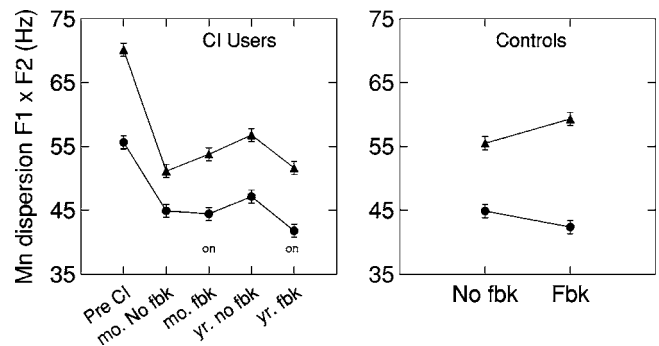


FIG. 3. Mean token dispersion in the formant plane for the five vowels elicited. For the implant users (left pane), dispersion is plotted as a function of the time sample, and presence (“ON”) or absence of auditory feedback during elicitation, with bite block insertion (triangles) as a parameter. For the speakers with normal hearing, the treatments were presence or absence of auditory feedback and of bite block (triangles). (For the cochlear implant users, each point is the mean of 800 determinations, 20 repetitions of each of 5 vowels produced by 8 speakers. For the hearing controls, each point is the mean of 700 determinations, 20 repetitions of 5 vowels produced by 7 speakers.) Error bars are one standard error of the mean.

the mean dispersion for that phoneme under the given experimental condition. To measure acoustic contrast distance, Mahalanobis distances were calculated for the ten possible pairs of five vowels, on each of twenty repetitions. Each repetition of a particular vowel on the i th trial is given a Mahalanobis distance to the distribution of each of the other vowels. The square roots of the distances were averaged for each group and listening condition.²

III. RESULTS

A. Dispersion

The average dispersion of vowel phones around their mean in the formant plane is plotted in Fig. 3, for implant users and hearing controls separately. For the implant users (left pane), dispersion is plotted as a function of the time sample, and presence (“ON”) or absence of auditory feedback during elicitation, with bite block insertion (triangles) as a parameter. For the hearing speakers, the treatments were presence or absence of auditory feedback and of bite block.

Hypothesis (1) states that the bite block will increase implant users' vowel dispersion. As the figure shows, it did so under all conditions of the experiment and especially before speakers had some hearing restored by cochlear prosthesis. Hypothesis (2), which states that the effect of the bite block will decline over time as the implant user gains experience with auditory feedback, is not supported: the effect of time sample (one month or one year after processor activation) and the time × bite block interaction are not significant. (The results of an ANOVA are reported in Table II). Hypothesis (3) states that vowel dispersion measured on speakers with normal hearing will increase less as a result of introducing the bite blocks than dispersion measured on implant users. These outcomes must be compared cautiously as the groups are small and differ in several respects, including gender and age. Contrary to the hypothesis, as Fig. 3 shows, the smaller increase in dispersion for the hearing controls, 10 Hz, was as large or larger than all the implant users' in-

TABLE II. Analysis of variance of dispersion measures for eight implant users (*= $p < 0.05$).

Source	df	F	Eta ² (%)
Between subjects	7 115	41.6*	71
Time sample	1 115	0.3	0.2
Time*subject	7 115	9.0*	35
Vowel	4 460	4.0*	3
Vowel*subject	28 460	3.2*	16
Feedback	1 115	5.7*	4
Feedback*subject	7 115	2.6*	13
Bite block	1 115	97.8*	45
Bite block*subject	7 115	12.6*	43
Time*vowel	4 460	2.1	1.7
Time*vowel*subject	28 460	3.7*	18
Time*feedback	1 115	3.5	2
Time*feedback*subject	7 115	2.2*	11
Time*bite block	1 115	1.3	1
Time*bite block*subject	7 115	5.6*	25
Vowel*feedback	4 460	0.4	0.3
Vowel*feedback*subject	28 460	2.8*	14
Vowel*bite block	4 460	6.3*	5
Vowel*bite block*subject	28 460	2.8*	14
Feedback*bite block	1 115	1.0	0
Feedback*bite block*subject	7 115	0.5	2
Time*vowel*feedback	4 460	2.9*	2
Time*vowel*feedback*subject	28 460	1.4	7
Time*vowel*bite block	4 460	2.1	1
Time*vowel*bite block*subject	28 460	2.7*	14
Time*feedback*bite block	1 115	0.1	0.1
Time*feedback*bite block*subject	7 115	2.7*	14
Vowel*feedback*bite block	4 460	1.1	0.9
Vowel*feedback*bite block*subject	28 460	1.3	7
Time*vowel*feedback*bite block	4 460	0.8	0.6
Time*vowel*feedback*bite block*subject	28 460	2.6*	13

creases in dispersion except for the preimplant condition. The mean increases were 13.7 Hz for the hearing subjects and 9.9 Hz for the implant users. The very high dispersion in the preimplant condition with no auditory feedback and bite blocks may be due to the elevated dispersion found without bite blocks in that condition. The increase in dispersion in that condition due to bite block, 26%, is comparable to the parallel increase obtained from the controls, 24%.

Hypothesis (4) states that dispersion of vowel tokens will be greater without auditory feedback than with it. It is supported by the findings with the implant users who yielded a significant effect of feedback condition (Table II), due primarily to their vowel dispersion measured one year after their implant speech processors had been activated. For the hearing speakers (Table III), the effects of interrupting auditory feedback on vowel dispersion depended on whether the bite blocks were present or not. Without bite blocks, dispersion was greater in the absence of feedback, consistent with hypothesis (4) ($F=3.8, df=7, 130, p < 0.01$). However, with bite blocks, dispersion was higher in the presence of feedback than in its absence ($F=5.8, df=7, 130, p < 0.01$), as was the case with the implant users in the one month sample.

To summarize: the bite blocks did indeed increase the dispersion of implant users' vowel phones, especially prior to their receiving their prostheses. However, there was no evi-

TABLE III. Analysis of variance of dispersion measures for seven control subjects with normal hearing (*= $p < 0.05$).

Source	df	F	Eta ² (%)
Between subjects	6 130	36.1*	62
Vowel	4 520	4.1*	3
Vowel*subject	24 520	3.6*	14
Feedback	1 130	0.0	0
Feedback*subject	6 130	3.6*	14
Bite block	1 130	86.0*	39
Bite block*subject	6 130	6.5*	23
Vowel*feedback	4 520	0.7	0.5
Vowel*feedback*subject	24 520	3.3*	13
Vowel*bite block	4 520	6.9*	5
Vowel*bite block*subject	24 520	2.0*	8
Feedback*bite block	1 130	4.7*	3
Feedback*bite block*subject	6 130	6.5*	23
Vowel*feedback*bite block	4 520	2.7*	2
Vowel*feedback*bite block*subject	24 520	3.2*	12

dence that this enlarged dispersion declined after greater experience hearing with the implant. Interrupting feedback did increase implant users' vowel dispersion but only in the one-year sample. It also increased the controls' dispersion but only without the bite blocks. The bite blocks were approximately equally disruptive for implant users and hearing controls.

B. Vowel contrast

Figure 4 presents a measure of speakers' compensations for the bite blocks. The vertical axes plot the average effect on F1 of inserting the bite block, compared to measures

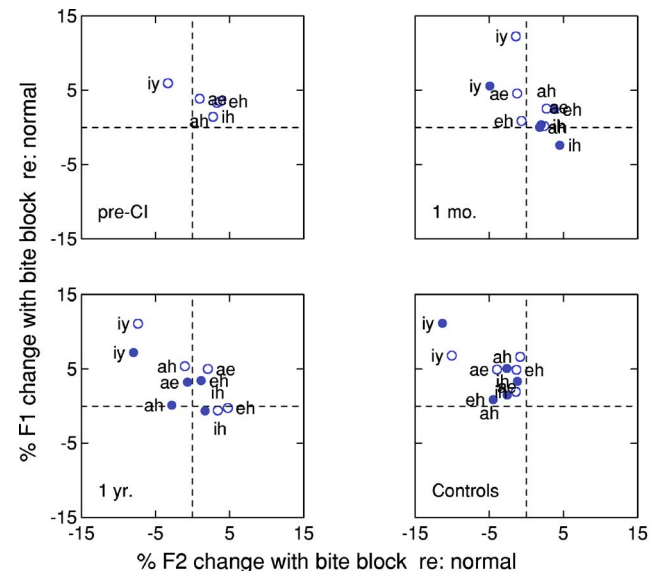


FIG. 4. (Color online) Compensation for bite block in three time samples for implant users and one for controls. The vertical axis plots the average effect on F1 of inserting the bite block, compared to measures without a bite block, and normalized by the latter (percent change). The horizontal axis plots the comparable measure for F2. Closed circles represent measures made with auditory feedback available; open, no feedback. (For the cochlear implant users, each point is the mean of 160 determinations, 20 repetitions by 8 speakers. For the hearing controls, each point is the mean of 140 determinations, 20 repetitions by 8 speakers.)

TABLE IV. Analysis of variance for the measures of average vowel space for implant users ($*=p<0.05$).

Source	<i>df</i>	<i>F</i>	<i>Eta</i> ² (%)
Between subjects	7 115	4 053*	99
Time sample	1 115	580*	83
Time*subject	7 115	1 354*	98
Vowel	4 460	11 900*	99
Vowel*subject	28 460	339*	95
Feedback	1 115	503*	81
Feedback*subject	7 115	515*	96
Bite block	1 115	14 500*	99
Bite block*subject	7 115	1 202*	98
Time*vowel	4 460	3*	2
Time*vowel*subject	28 460	29*	63
Time*feedback	1 115	1 824*	94
Time*feedback*subject	7 115	410*	96
Time*bite block	1 115	114*	49
Time*bite block*subject	7 115	576*	97
Vowel*feedback	4 460	28*	19
Vowel*feedback*subject	28 460	28*	63
Vowel*bite block	4 460	679*	85
Vowel*bite block*subject	28 460	50*	75
Feedback*bite block	1 115	516*	81
Feedback*bite block*subject	7 115	250*	93
Time*vowel*feedback	4 460	56*	32
Time*vowel*feedback*subject	28 460	18*	52
Time*vowel*bite block	4 460	50*	30
Time*vowel*bite block*subject	28 460	13*	44
Time*feedback*bite block	1 115	6*	4.9
Time*feedback*bite block*subject	7 115	186*	91
Vowel*feedback*bite block	4 460	20*	14
Vowel*feedback*bite block*subject	28 460	5*	23
Time*vowel*feedback*bite block	4 460	1	0.8
Time*vowel*feedback*bite block*subject	28 460	10*	37

without a bite block, and normalized by the latter (in percent) (“re: normal”). The horizontal axis plots the comparable measure for F2. Closed circles represent measures made with auditory feedback available; open, no feedback. The finding that most points lie within a few percent of the dotted lines at $F1 \% \text{ change}=0$ and $F2 \% \text{ change}=0$ indicates that our speakers, both implant users and controls, compensated for the bite block in a way that allowed them nearly to restore their formant frequencies in the unperturbed state. Nevertheless, the mean percent changes in F1 and F2, pooling across subjects and vowels (N =approximately 750 values) were significantly different from zero in every case but one (viz., F2 at one year without feedback). Those changes were, on average, almost identical comparing feedback and no feedback conditions. Not surprisingly, /i/ is one of the vowels most resistant to compensation as it is the vowel with the highest place of articulation in this study and thus particularly hindered by its 2.5 cm bite block.

The effects of the experimental interventions on the vowel space will be seen in Fig. 5 and Table IV. Findings for implant users and controls are shown separately. The average size of the vowel space (AVS) is expressed as the average Mahalanobis distance between the members of all ten possible pairs of the five vowels. For the implant users (left pane), AVS is plotted as a function of the time sample, and

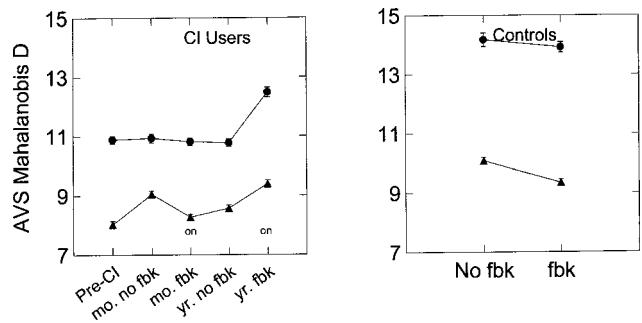


FIG. 5. The average size of the vowel space (AVS) is expressed as the mean of (the square root of) the Mahalanobis distances between the members of all ten possible pairs of the five vowels. For the implant users (left pane), AVS is plotted as a function of the time sample, and presence (“ON”) or absence of auditory feedback during elicitation, with bite block insertion (triangles) as a parameter. For the controls, the treatments were presence or absence of auditory feedback and of bite block (triangles). (For the cochlear implant users, each point is the mean of 800 determinations of average vowel spacing. The 4 distances from each vowel token to the other tokens in each repetition set were averaged, and a grand mean obtained for the 20 repetitions of each of the 5 vowels produced by 8 speakers. For the hearing controls, each point is the mean of 700 determinations, 20 repetitions of 5 vowels produced by 7 speakers.) Error bars are one standard error of the mean.

presence (“ON”) or absence of auditory feedback during elicitation, with bite block insertion (triangles) as a parameter. For the controls, the treatments were the presence or absence of auditory feedback and of bite block (Table V).

Hypothesis (5) states that the insertion of a bite block will reduce the distances in the formant plane separating vowels. It is supported by visual inspection of Fig. 5, where the triangles fall below the circles in both panes, and by ANOVAs for both groups of speakers. Hypothesis (6) states that the reduction in size of the vowel space due to the bite block will be less for the controls than for the implant users. This expectation is clearly not borne out, whether one measures the decrease in AVS in absolute terms (4.3 units for controls, 2.5 for implant users, averaging across all values) or relative terms (31% for controls, 22% for implant users). The reduction in the controls’ vowel space with a bite block appears to be so large, compared to the implant users, at least in part because they had a larger vowel space in the first place (14.0 vs 11.2 units). This view is supported by the observation that AVS for the controls with a bite block is higher than the AVS for implant users with a bite block (9.7 units vs 9.0), despite the bigger percent reduction in AVS for normal-hearing speakers ($t=4.2, df=199, p<0.01$).

Hypothesis (7) states that vowel contrast will improve after extended implant use. Figure 5 shows that with auditory feedback (indicated by “on”), the size of the implant users’ vowel space increased from one month to one year (both with and without bite block). However, without feedback no such improvement appeared: the vowel space was unchanged in size (no bite blocks, $t=1.2, df=784, p=0.25$) or became a half unit smaller (bite blocks, $t=5.7, df=783, p<0.01$). Examining normal-hearing speakers’ productions of /s/ with and without masking while they wore a dental prosthesis, Jones and Munhall (2003) report a parallel result: There was improvement in compensating for the prosthesis but only when speakers could hear their speech.

TABLE V. Analysis of variance for the measures of average vowel space for control speakers with normal hearing (*= $p < 0.05$).

Source	<i>df</i>	<i>F</i>	Eta ² (%)
Between subjects	6 130	3 574*	99
Vowel	4 520	9 921*	98
Vowel*subject	24 520	208*	90
Feedback	1 130	257*	66
Feedback*subject	6 130	1 517*	98
Bite block	1 130	25 100*	99
Bite block*subject	6 130	1 269*	98
Vowel*feedback	4 520	65*	33
Vowel*feedback*subject	24 520	36*	62
Vowel*bite block	4 520	964*	88
Vowel*bite block*subject	24 520	70*	76
Feedback*bite block	1 130	78*	37
Feedback*bite block*subject	6 130	1 492*	98
Vowel*feedback*bite block	4 520	5*	3
Vowel*feedback*bite block*subject	24 520	23*	51

Hypothesis (8) states that the size of the vowel space will be greater with auditory feedback than without it. This was confirmed by measures taken, both with and without bite blocks, at implant users' one year session but was not observed at the one month session where, on the contrary, AVS with bite blocks inserted was larger in the absence of feedback ($t=15.3, df=787, p < 0.01$). Likewise, the controls showed significantly larger vowel spaces without auditory feedback across bite block condition (Table V).

To summarize: the implant users and hearing controls in this experiment did not compensate fully for the shift in formant values caused by insertion of the bite blocks. Consequently there were net changes to the size of the vowel space and those changes varied with the samples of time since implantation and the presence or absence of auditory feedback. The insertion of the bite blocks did indeed reduce the distances separating vowels for both groups. However, the hearing controls did not appear to be better compensators; on the contrary, they had greater compression of the vowel space in both relative and absolute terms, though their AVS with the bite block was still higher than that for the implant users with the bite block. The implant users' vowel spaces had grown by the one-year session but not in the first month. Finally, interrupting implant users' auditory feedback at one year led to a reduction in their vowel spaces, consistent with the hypothesis, but interruption produced the opposite effect in the controls.

IV. DISCUSSION

A. Dispersion

The dispersion of vowel tokens around their means (Fig. 3) was substantially increased by insertion of the bite blocks, confirming hypothesis (1). For the implant users, dispersion of vowel productions was highest before they received prosthetic hearing; at this time most of the speakers had too little audition to distinguish among vowels and that had been the case for some years. Then the bite blocks were introduced exacerbating the already elevated vowel dispersion. In terms

of the model in Fig. 1, the deaf speakers' poor discriminative capacity deprived them of accurate auditory error signals (box 3) that would otherwise modify future feedforward commands (setting aside for now the issue of closed-loop error correction within a syllable). The lack of an auditory error signal caused the deaf speakers to produce a greater range of trajectories (Fig. 2) passing through the phonemic goal regions, and that greater range was reflected in the mid-vowel formant measures and thus in the measured dispersion. Despite this variability, the late-deafened speakers compensated astonishingly well to bite blocks after decades with degraded or no auditory feedback (cf., Fig. 4). This may be a reflection of goal regions that are highly stable over time and over feedback conditions, while the changes in dispersion due to bite block and changes in feedback may be attributable to changes in trajectories passing through the outskirts of those goal regions. The DIVA model postulates that goal regions and feedforward commands degrade very slowly over time with extensive hearing loss. [On the stability of the goal regions, see Perkell *et al.* (1992).]

Consistent with our findings, the sole study of the effects of bite block on late-deafened adults that has come to our attention (Tye *et al.*, 1983) reports that two deaf speakers showed more variable tongue shapes and positions, both with and without bite blocks, than did three hearing controls. The dramatic drop in implant users' vowel dispersion in the present study that occurred a month after they had some hearing restored, and the long-term decrease of their dispersion into the normal range, confirm that auditory feedback reduces production variability (Harris *et al.*, 1985; McGarr and Campbell, 1995), possibly by making trajectories smoother and more accurate.

One month of auditory experience with the implant markedly reduced dispersion both with and without the bite blocks. The enlarged vowel dispersion due to the bite blocks did not diminish significantly as the implant users gained auditory experience from one month to one year (Fig. 3), disconfirming hypothesis (2). (If auditory feedback were a guarantor of reduced variability, the speakers with normal hearing would not have increased dispersion as much as they did with the introduction of the bite block.) At one year after activation of their speech processors, however, implant users' dispersion reached a minimum without the bite blocks, indicating a greater role for auditory feedback after longer experience with the implant.

The controls were also more variable in their vowel productions with introduction of the bite blocks. The increase in their dispersion compared to their vowel productions without bite blocks was not less than that of implant users, contrary to hypothesis (3).

Finally, do short-term interruptions of auditory feedback increase vowel token dispersion, as hypothesis (4) posits? The answer is a qualified "yes." For the implant users, dispersion was greater without auditory feedback in the sample at one year but not that at one month. Auditory feedback may not have reduced dispersion at one month because prosthetic feedback is quite different from the speaker's former auditory feedback. Thus it takes some time before the auditory system reorganizes to the point where it can make use of the

new auditory information for guiding speech. For the control speakers, dispersion without bite blocks was also greater without auditory feedback. However, with the bite blocks in place, the controls' vowel dispersion was unexpectedly less without feedback than with it, possibly because speakers had adopted a "clear speech" strategy in the face of bite blocks and no feedback (Lane and Tranel, 1971; Picheny *et al.*, 1986).

B. Vowel contrast

Tye *et al.* (1983) found that two deaf speakers (one congenitally deaf, the other postlingually deaf), exhibited articulatory compensation for a bite block. Campbell (1999) reported that a group of six congenitally, profoundly deaf speakers not only compensated but in fact overcompensated for a bite block in production of high vowels. In the present study, the implant users' compensation for the bite blocks was excellent (Fig. 4), with most vowel means falling within 5% of perfect compensation. It is questionable whether the implant users, given the limited fidelity of their prosthetic hearing, were able to detect that they had undercompensated. With speakers having normal hearing, Baum *et al.* (1996) found no effect of bite block on the speaker's vowel intelligibility and rated vowel quality (except for /i/). Fowler and Turvey (1980) found that bite block vowels were slightly less identifiable than unperturbed vowels for three of their four speakers, but the bite block had a substantial effect on vowel identification with only one speaker.

The significant shortfall in bite block compensation that remained after our speakers' compensatory movements is reflected in the average vowel spacing as a reduction (Fig. 5), as predicted by hypothesis (5). Turning to the control speakers, Fig. 5 shows that with bite blocks in place they also reduced their vowel spaces but to a much greater degree than the implant users thus disconfirming hypothesis (6) that their vowel contrast would be less affected than that of the implant users.

There is evidence, confirming hypothesis (7), that vowel contrast improved with extended use of the auditory prosthesis: with auditory feedback, the average vowel space grew from the one-month to the one-year sample (Fig. 5) both with and without bite blocks. With sustained auditory feedback and hearing speakers, Baum *et al.* (1996) found that 15 min of conversation with bite blocks in place enhanced compensation. Flege *et al.* (1988) obtained a similar result. We examined our data for a short-term practice effect by comparing percent bite block compensation on the first and last (twentieth) trial in the one-month and one-year samples; however, we found none. Most likely, it was the extended experience with their prostheses that led implant users to increase contrast distance by the time of the one-year sample. Economou *et al.* (1992) reported on a postlingually deaf pre-adolescent who had a failed single-channel implant replaced by a multichannel device. Eighteen days after the failure of the single-channel implant, his vowel space was reduced and after a year's experience with the multichannel implant, it was significantly expanded.

Was the measured vowel space smaller without auditory

feedback than with it, as hypothesis (8) claims? This proved to be true of the implant users at one year (but not at one month). Svirsky *et al.* (1992) found with implant users that vowel contrast decreased when auditory feedback was interrupted and expanded when it was restored. Matthies *et al.* (1996) reported contrast reductions for fricatives with interrupted auditory feedback in implant users and Lane *et al.* (1995) found the same for plosive voicing.

However, turning to the speakers in the present study with normal hearing, Fig. 5 shows they did not have smaller vowel spaces when their auditory feedback was masked. It is possible that there were differences among the vowels that their two-formant specification did not capture. In the study cited earlier of /s/ productions while wearing a dental prosthesis, Jones and Munhall (2003) found the spectra of the speakers' /s/ productions moved toward that of normal, unperturbed production with increased experience with the prosthesis. Although an acoustic analysis did not show any significant differences depending on auditory feedback, listener ratings proved to be higher for utterances recorded with feedback present.

C. Relating the results to the DIVA model

The disconfirmed hypotheses from these experiments suggest refinements to the DIVA model. In particular, disconfirmation of hypothesis (8) for speakers with normal hearing (they did *not* show greater vowel spacing with auditory feedback) suggests that a change in hearing status may not immediately change average vowel spacing. Instead, hearing status appears to affect average vowel spacing more slowly, as evidenced by the larger AVS of normal-hearing speakers (with or without auditory feedback) compared to the AVS of the deaf speakers prior to implantation (cf. Fig. 5). With regard to the DIVA model, this suggests that the greater vowel space of normal-hearing speakers relative to the deaf is not due to the hearing speakers' online feedback control mechanisms (otherwise AVS would have increased with auditory feedback in these speakers), but instead due to the slow degradation of the deaf speakers' feedforward commands. Currently the DIVA model does not explicitly include degradation of feedforward commands in the absence of auditory feedback unless the vocal tract morphology changes; instead the commands remain tuned indefinitely when feedback is removed.³ Such degradation could be incorporated by including a very slow decay term for the synaptic weights encoding feedforward commands in the model.

One year after implantation, implant users still show a relatively small AVS in the absence of auditory feedback, but their AVS increases when the implant is turned on. This suggests that their feedforward commands are still not fully tuned, but experience with the implant has allowed them to learn new auditory targets (corresponding to the initially novel auditory signals produced by the implant), which in turn allows their auditory feedback control subsystems to perform online corrections to their still-degraded feedforward commands. According to the DIVA model, continued practice should eventually lead to improved feedforward commands in these individuals due to this corrective influ-

ence of the auditory feedback control circuit. If this account is correct, this process apparently takes longer than one year.

Disconfirmation of hypothesis (6) (that the reduction in vowel space due to bite block insertion will be smaller for controls than for implant users) appears to be largely explained by the observation that AVS is much larger for controls than implant users before bite block insertion, and thus the reduced range of motion caused by the bite blocks is more disruptive in controls. The greater AVS of hearing speakers compared to deaf speakers is consistent with the idea, outlined in the previous paragraph, that the feedforward commands of hearing-impaired individuals become degraded slowly over time, leading to a reduction of vowel spacing.

Disconfirmation of hypothesis (3) (which states that the effect of the bite block on vowel dispersion should be less for normally hearing speakers than implant users) appears to indicate that hearing does not significantly affect the increased dispersion of vowel tokens caused by a bite block, even after long periods of time with little or no hearing. That is, both hearing and bite block affect dispersion but there is no significant interaction (cf. Table II for confirmation). If hearing does not affect bite block-induced dispersion, this would also account for the disconfirmation of hypothesis (2) (that the deleterious effect of the bite block on vowel dispersion will decrease with time after implantation) and hypothesis (4) (that auditory feedback should reduce the effect of the bite block on dispersion). In the DIVA model, many factors can affect the dispersion of repeated vowel tokens, including (i) size and location of the auditory target region for the vowel, (ii) phonetic context, (iii) change in speaking style and/or rate, (iv) presence or absence of articulator perturbations such as bite blocks, and (v) presence or absence of auditory feedback. Because the dynamics of the model depend in a complex way on each of these factors, their net effect on variability can only be determined through computer simulations of the model on the specific tokens and conditions of the experiment, which is beyond the scope of the current article.

D. Summary

In order to explore the role of audition during speech production, several interventions were made with postlingually deaf speakers and hearing controls: the deaf speakers received cochlear implants and were tested before, one month after, and one year after activation of their speech processors. Both groups received bite blocks and short-term interruptions of auditory feedback. Our theoretical framework assigned to auditory feedback the role of revising feedforward commands controlling trajectories between phoneme goals. With long-term absence of auditory feedback, dispersion of vowel tokens was expected to be large and inflated further by inserting bite blocks, as speakers would have no way to adequately inform themselves of their auditory effects. Once these speakers receive cochlear prostheses, they should be able to use auditory feedback and the dispersion would fall. These expectations were supported. To a degree, the effects of short-term interruptions of feedback paralleled these long-term changes.

The deaf speakers compensated extensively, even before they had prosthetic hearing; however, the compensation was not total. Consequently, insertion of the bite blocks reduced the size of their vowel spaces. The vowel space had grown when it was measured with auditory feedback present a year after processor activation, both without and with bite blocks. Two processes may have been at work after a year of audition: improved vowel contrasts (seen in the no bite block condition) and improved compensation for the bite block perturbation.

Thus auditory experience with a prosthesis brought a reduction of the heightened dispersion when deaf. It reduced dispersion over a year (Fig. 3) and also expanded the vowel space (Fig. 5). These findings indicate that any model of speech production must assign a role to auditory feedback in error-based correction of feedforward commands for subsequent articulatory gestures.

ACKNOWLEDGMENTS

This research was supported by Grant No. R01-DC003007 from the National Institute on Deafness and Other Communication Disorders, National Institutes of Health. We are grateful to Dr. Donald Eddington of the Massachusetts Eye and Ear Infirmary and Dr. Daniel Lee of the Department of Otolaryngology—Head and Neck Surgery, University of Massachusetts Medical School for referring cochlear implant users to our study. We acknowledge the assistance of Satrajit Ghosh.

¹There is a body of literature showing compensatory responses to alterations in auditory feedback, consistent with the hypothesis that it serves to correct perceived errors produced by feedforward commands. However, it remains unclear when auditory feedback updates feedforward commands for the next utterance and when it introduces corrections during a speech sound. Among the variables that have been manipulated with compensatory consequences are amplitude (Lane and Tranel *et al.*, 1971; Siegel *et al.*, 1982); fundamental frequency (Kawahara and Williams, 1996; Burnett *et al.*, 1998; Hain *et al.*, 2001; Natke and Kalveram, 2001); and vowel spectra (Houde and Jordan, 1998, 2002).

²The Mahalanobis Distance, D^2 , is defined as $(x_i - y_i)' S^{-1} (x_i - y_i)$, where x are the individual's scores on a number of measures, y are the corresponding means from a prespecified group, S^{-1} is the inverse covariance matrix. Unlike Euclidean distance, D^2 takes into account not only the average value but also the variance and covariance of the variables measured and it does not assume equal weight for the two predictors, F1 and F2. D^2 measures the overlap of two distributions; it is the basis of a maximum probability classification; and is proportionate to the F ratio as a measure of separation (Taguchi and Jugulum, 2002).

³In simulations to date, once the DIVA model has been tuned with a particular vocal tract morphology, removing auditory feedback does not affect the learned target regions, and the feedforward commands remain in their current state unless the vocal tract morphology changes. If such changes occur, the somatosensory feedback subcircuit will cause changes in the feedforward commands, and in the absence of the auditory feedback subcircuit, these changes may be deleterious to the acoustic signal. This may be responsible for the degraded vowel spacing found in pre-implant measurements, but this is impossible to verify without measurements indicating the amount of change in morphology since onset of deafness.

Baum, S. R., McFarland, D. H., and Diab, M. (1996). "Compensation to articulatory perturbation: Perceptual data," *J. Acoust. Soc. Am.* **99**, 3791–3794.

Blamey, P. J., Dowell, R. C., Brown, A. M., Clark, G. M., and Seligman, P. M. (1987). "Vowel and consonant recognition of cochlear implant patients using formant-estimating speech processors," *J. Acoust. Soc. Am.* **82**,

- Burnett, T. A., Freedland, M. B., Larson, C. R., and Hain, T. C. (1998). "Voice F0 responses to manipulations in pitch feedback," *J. Acoust. Soc. Am.* **103**, 3153–3161.
- Campbell, M. (1999). "Articulatory compensation for a biteblock, with and without auditory feedback in hearing and hearing-impaired speakers," Doctoral dissertation, City University of New York (unpublished).
- Economou, A., Tarter, V., Chute, P., and Hellman, S. (1992). "Speech changes following reimplantation from a single-channel to a multichannel cochlear implant," *J. Acoust. Soc. Am.* **92**, 1310–1323.
- Flege, J. E., Fletcher, S. G., and Homiedan, A. (1988). "Compensating for a bite block in /s/ and /t/ production: Palatographic, acoustic, and perceptual data," *J. Acoust. Soc. Am.* **83**, 212–228.
- Fowler, C. A., and Turvey, M. T. (1980). "Immediate compensation in bite-block speech," *Phonetica* **37**, 306–326.
- Guenther, F., and Perkell, J. (2004). "A neural model of speech production and its application to studies of the role of auditory feedback in speech," in *Speech Motor Control in Normal and Disordered Speech*, edited by B. Maassen, R. Kent, H. F. M. Peters, P. Lieshout, and W. Hulstijn (Oxford University Press, Oxford), pp. 29–50.
- Guenther, F. H. (1994). "A neural network model of speech acquisition and motor equivalent speech production," *Biol. Cybern.* **72**, 43–53.
- Guenther, F. H. (1995). "Speech sound acquisition, coarticulation, and rate effects in a neural network model of speech production," *Psychol. Rev.* **102**, 594–621.
- Guenther, F. H., Hampson, M., and Johnson, D. (1998). "A theoretical investigation of reference frames for the planning of speech movements," *Psychol. Rev.* **105**, 611–633.
- Hain, T. C., Burnett, T. A., Larson, C. R., and Kiran, S. (2001). "Effects of delayed auditory feedback (DAF) on the pitch-shift reflex," *J. Acoust. Soc. Am.* **109**, 2146–2152.
- Harris, K. S., Rubin-Spitz, J., and McGarr, N. (1985). "The role of production variability in normal and deviant developing speech," *ASHA Reports* **15**, 50–57.
- Hoole, P. (1987). "Bite-block speech in the absence of oral sensibility," in *Proceedings of the XIth International Congress of Phonetic Sciences Tallinn*, pp. 16–19.
- Houde, J. F., and Jordan, M. I. (1998). "Sensorimotor adaptation in speech production," *Science* **279**, 1213–1216.
- Houde, J. F., and Jordan, M. I. (2002). "Sensorimotor adaptation of speech. I. Compensation and adaptation," *J. Speech Lang. Hear. Res.* **45**, 295–310.
- Jones, J. A., and Munhall, K. G. (2003). "Learning to produce speech with an altered vocal tract: The role of auditory feedback," *J. Acoust. Soc. Am.* **113**, 532–543.
- Kawahara, H., and Williams, J. C. (1996). "Effects of auditory feedback on voice pitch trajectories: Characteristic responses to pitch perturbations," in *Vocal fold Physiology*, edited by P. J. Davis and N. H. Fletcher (Singular, San Diego), pp. 263–278.
- Lane, H., Matthies, M., Denny, M., Guenther, F. H., Perkell, J. S., Stockmann, E. *et al.* (2005). "Effects of short- and long-term changes in auditory feedback on vowel and sibilant contrasts," *Ear Hear.* (submitted).
- Lane, H., and Tranel, B. (1971). "The Lombard sign and the role of hearing in speech," *J. Speech Hear. Res.* **14**, 677–709.
- Lane, H., Wozniak, J., Matthies, M., Svirsky, M., and Perkell, J. (1995). "Phonemic resetting vs. postural adjustments in the speech of cochlear implant users: An exploration of voice-onset time," *J. Acoust. Soc. Am.* **98**, 3096–3106.
- Lindblom, B. (1990). "Explaining phonetic variation: A sketch of the H & H theory," in *Speech Production and Speech Modeling*, edited by W. J. Hardcastle and A. Marchal (Kluwer, Dordrecht), pp. 403–439.
- Lindblom, B., Lubker, J., and Gay, T. (1978). "Formant frequencies of some fixed mandible vowels and a model of speech motor programming by predictive simulation," *J. Phonetics* **7**, 147–161.
- Lindblom, B. E., and Sundberg, J. E. (1971). "Acoustical consequences of lip, tongue, jaw, and larynx movement," *J. Acoust. Soc. Am.* **50**, 1166–1179.
- Lindblom, B. E. F. (1980). "Phonetic universals in vowel systems," in *Experimental Phonology*, edited by J. J. Ohala and J. J. Jaeger (Academic, Orlando, FL), pp. 13–44.
- Lubker, J. F. (1979). "The reorganization times of bite-block vowels," *Phonetica* **36**, 273–293.
- Matthies, M., Svirsky, M., Perkell, J., and Lane, H. (1996). "Acoustic and articulatory measures of sibilant production with and without auditory feedback from a cochlear implant," *J. Speech Hear. Res.* **39**, 936–946.
- McFarland, D. H., and Baum, S. R. (1995). "Incomplete compensation to articulatory perturbation," *J. Acoust. Soc. Am.* **97**, 1865–1873.
- McGarr, N. S., and Campbell, M. (1995). "Ephphatha: Opening inroads to understanding articulatory organization in persons with hearing impairment," in *Producing Speech: Contemporary Issues: For Katherine Safford Harris*, edited by F. Bell-Berti and L. Raphael (AIP Press, New York), pp. 433–404.
- McKay, C. M., and McDermott, H. J. (1993). "Perceptual performance of subjects with cochlear implants using the spectral maxima sound processor (SMSP) and the mini speech processor (MSP)," *Ear Hear.* **14**, 350–367.
- Natke, U., and Kalveram, K. T. (2001). "Effects of frequency-shifted auditory feedback on fundamental frequency of long stressed and unstressed syllables," *J. Speech Lang. Hear. Res.* **44**, 577–584.
- Perkell, J., Lane, H., Svirsky, M., and Webster, J. (1992). "Speech of cochlear implant patients: A longitudinal study of vowel production," *J. Acoust. Soc. Am.* **91**, 2961–2978.
- Picheny, M. A., Durlach, N. I., and Braida, L. D. (1986). "Speaking clearly for the hard-of-hearing II. Acoustic characteristics of clear and conversational speech," *J. Speech Hear. Res.* **29**, 434–446.
- Siegel, G. M., Schork, E. J., Pick, H. L., and Garber, S. R. (1982). "Parameters of auditory feedback," *J. Speech Hear. Res.* **25**, 473–475.
- Svirsky, M., Lane, H., Perkell, J., and Wozniak, J. (1992). "Effects of short-term auditory deprivation on speech production in adult cochlear implant users," *J. Acoust. Soc. Am.* **92**, 1284–1300.
- Taguchi, G., and Jugulum, R. (2002). *The Mahalanobis-Taguchi Strategy: A Pattern Technology System* (Wiley, New York).
- Tye, N., Zimmermann, G., and Kelso, S. (1983). "'Compensatory articulation' in hearing-impaired speakers: A cinefluorographic study," *J. Phonetics* **11**, 101–115.
- Wilson, B., Lawson, D., Zerbi, M., Finley, C., and Wolford, R. (1995). "New processing strategies in cochlear implantation," *Am. J. Otol.* **16**, 669–681.