Interactions of speaking condition and auditory feedback on vowel production in postlingually deaf adults with cochlear implants[a]

Lucie Ménard[b]
Département de Linguistique, Université du Québec à Montréal, Montréal (Québec), H3C 3P8 Canada and Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Marek Polak
Department of Otolaryngology, University of Miami Medical School, Miami, Florida 33149

Margaret Denny
Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Ellen Burton
Applied Public Health, Johns Hopkins Bloomberg School of Public Health, Baltimore, Maryland 21205 and Maryland Association of County Health Officers, Baltimore, Maryland 21205

Harlan Lane
Department of Psychology, Northeastern University, Boston, Massachusetts and Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Melanie L. Matthies and Nicole Marrone
Department of Speech, Language and Hearing Sciences, Boston University, Boston, Massachusetts, and Speech Communication Group, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Joseph S. Perkell
Speech Communication Group, Research Laboratory of Electronics, and Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 and Department of Cognitive and Neural Systems, Boston University, Boston, Massachusetts 02115

Mark Tiede
Speech Communication Group Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 and Haskins Laboratories, New Haven, Connecticut 06511

Jennell Vick
Department of Speech and Hearing Sciences, University of Washington, Seattle, Washington 98015

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This study investigates the effects of speaking condition and auditory feedback on vowel production by postlingually deafened adults. Thirteen cochlear implant users produced repetitions of nine American English vowels prior to implantation, and at one month and one year after implantation. There were three speaking conditions (clear, normal, and fast), and two feedback conditions after implantation (implant processor turned on and off). Ten normal-hearing controls were also recorded once. Vowel contrasts in the formant space (expressed in mels) were larger in the clear than in the fast condition, both for controls and for implant users at all three time samples. Implant users also produced differences in duration between clear and fast conditions that were in the range of those obtained from the controls. In agreement with prior work, the implant users had contrast values lower than did the controls. The implant users' contrasts were larger with hearing on than off and improved from one month to one year postimplant. Because the controls and implant users responded similarly to a change in speaking condition, it is inferred that auditory feedback, although demonstrably important for maintaining normative values of vowel contrasts, is not needed to maintain the distinctiveness of those contrasts in different speaking conditions. © *2007 Acoustical Society of America.*

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[a] This study was conducted in collaboration with the Dept. of Otolaryngology, University of Miami Medical School, Miami, Florida.

[b] Author to whom correspondence should be addressed. Electronic mail: menard@speech.mit.edu

I. INTRODUCTION

The production of speech can be thought of in terms of a trade-off between two competing constraints, namely the need to ensure intelligibility and the tendency to minimize effort (Lindblom, 1990; Guenther *et al.*, 1998; Perkell *et al.*, 2000). When asked to speak clearly, speakers put more weight on intelligibility requirements (cf. Picheny *et al.*, 1985, 1986; Liu *et al.*, 2004; Chen, 1980; Krause and Braida, 2004; Payton *et al.*, 1994; Ferguson and Kewley-Port, 2002). On the other hand, instructions to speak rapidly tend to induce a speaker to rely on a strategy dominated by minimizing effort (Perkell *et al.*, 2000). Previous studies have shown that varying speaking condition greatly influences the acoustic properties of vowels and consonants (e.g., Krause and Braida, 2004). For normal-hearing speakers, clear speech—in comparison to conversational speech—is characterized, among other respects, by longer sound segments, tighter acoustic clustering within vowel categories, expanded vowel spaces and greater voice onset time (VOT) contrasts (Picheny *et al.*, 1986; Moon and Lindblom, 1994; Moon, 1991). However, the extent to which these contrasts are affected by speaking condition varies considerably across speakers (cf. Perkell *et al.*, 2000).

Previous research on the speech of cochlear implant users conducted by our group and others has provided a large body of evidence that those phonetic parameters affected by variations in speaking condition (acoustic distance between vowels, acoustic clustering within vowel categories, and vowel duration) are also affected by degradation of auditory feedback (Vick *et al.*, 2001; Perkell *et al.*, 2001; Svirsky and Tobey, 1991; Lane *et al.*, 2005; Lane *et al.*, 1995; Perkell *et al.*, 2007). Speakers who become profoundly deaf postlingually usually continue to produce intelligible speech for years or even decades following hearing loss, hypothetically due to the robustness of feedforward commands (commands that are executed without regard for sensory feedback) and somatosensory phonemic goals they acquired while they could hear (cf. Guenther *et al.*, 2006). Nevertheless, such speakers do experience some gradual degradation of their speech, presumably as a result of some deterioration of acquired auditory phonemic goals and feedforward commands. Compared to normal hearing speakers, postlingually deafened speakers produce decreased spectral contrast distances among vowels (Vick *et al.*, 2001; Perkell *et al.*, 2001; Svirsky and Tobey, 1991), increased vowel dispersion in the formant space (Lane *et al.*, 2005), and increased vowel duration (Lane *et al.*, 1995). In this paper, *contrast distance* for two vowels is defined as the Euclidean distance between them in the formant space. When more than one vowel pair is studied, *average vowel spacing* is the mean of all possible intervowel Euclidean distances in the formant space. For multiple repetitions of a given vowel, *vowel dispersion* is defined as the mean of the Euclidean distances, in the formant space, between each repetition and the target mean of all repetitions.

When deaf speakers have some hearing restored with cochlear implants, their vowel and consonant recognition scores increase significantly as early as 1 month postimplant. However, those speakers may show little improvement—or even some diminution—in produced contrast distances compared to the pre-implant stage (Lane *et al.*, 2006). Presumably these deaf speakers have not had enough experience with the new auditory feedback to update their feedforward commands adequately. After an extended period of implant use, however (1 year, for instance), speakers apparently have retuned their auditory feedback and have begun to use the new auditory feedback to retune their feedforward commands. By one year postimplant, contrast distances have increased, while vowel token dispersions in the formant space have decreased, and vowel durations have decreased in the direction of normative values (Schenk *et al.*, 2003; Langereis *et al.*, 1998; Vick *et al.*, 2001; Economou *et al.*, 1992; Smyth *et al.*, 1991; Lane *et al.*, 2005, 2006). Even when auditory feedback is interrupted by switching the implant processor off, vowel contrasts remains greater and vowel dispersions lower than at the pre-implant stage (Lane *et al.*, 2005, 2006). Taken together, these studies show that contrast distances, token dispersions around the vowel type mean, and vowel durations are altered by variation in speaking condition and by deprivation of auditory feedback. This study explores further the interaction between those independent and dependent variables.

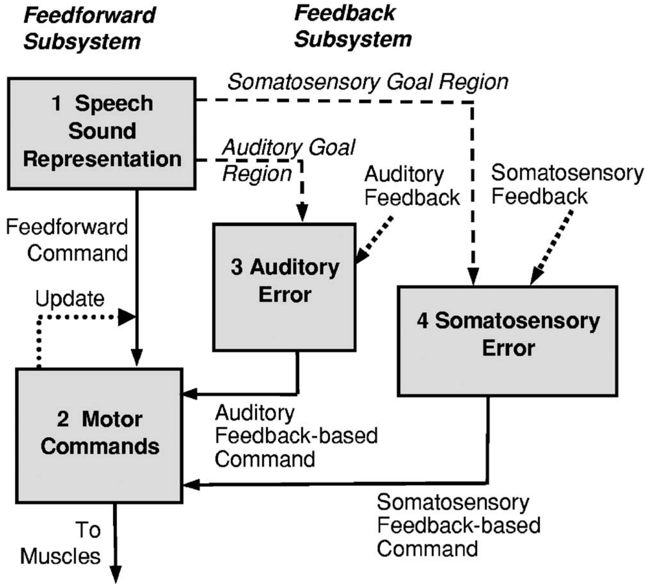

FIG. 1. Schematic diagram of the functionality of the DIVA model.

A. Theoretical background

The present study was guided by the Directions into Velocities of Articulators (DIVA) model (Guenther, 1995; Guenther *et al.*, 1998, 2006), a neuro-computational model of speech motor planning (see Fig. 1). In this model, phonemes are encoded in terms of goals in a multidimensional sensory space (auditory and somatosensory). Speech sounds are produced through the use of feedback and feedforward control systems. In the feedback system, sensory goals are compared to the current sensory state, and error signals arise if there is a mismatch (dotted arrows in Fig. 1). In this model, removal of auditory feedback (by switching the im-

TABLE I. Predicted differences in the dependent variables as a function of the independent variables.

Independent variables	Speaking condition (controls)	Hearing status	Time post-implant	Hearing state
Dependent variables	Clear compared to conversational speech	Postlingually deaf compared to normal hearing	Implant users at one year post-implant compared to pre-implant	Implant users with processor on compared to processor off
Vowel contrast distance	Higher	Lower	Higher	Higher
Vowel dispersion	Lower	Higher	Lower	Lower
Vowel duration	Higher	Higher	Lower	Lower

plant processor off, for instance) leads the model to rely on feedforward commands, in combination with somatosensory feedback control. In the short term, this degrades speech only slightly since the feedforward subsystem is still well tuned. However, if hearing loss continues for a long period (years, for instance), the feedforward commands degrade slowly. This degradation would be accelerated if changes in vocal tract morphology invalidate the speaker's existing feedforward commands.

Deterioration of speech motor control can be observed as reduced acoustic contrast distances between speech sounds, and/or increased token dispersions around the mean. When feedback is restored, the speaker's task is first to retune the auditory feedback control subsystem, by re-defining auditory targets and relearning corrective mechanisms. As reported in previous studies, new implant users characteristically have low scores on word recognition tests (see Tyler *et al.*, 1997). As their acuity for discriminating those sounds improves with prosthesis use, they can relearn auditory goals for their speech as well as new mappings between auditory errors and the changes in speech movements that will correct them. As auditory feedback becomes more accurate, the speaker is able to use corrective motor commands based on that auditory feedback to recalibrate the feedforward commands. The DIVA model's account of feedback and feedforward interactions in speech production is used here as a framework for making predictions and interpreting results.

B. Objective

To our knowledge, no study has focused on the combined effects of speaking condition and auditory feedback on contrast distance, vowel dispersion, and vowel duration. Our objective is thus to determine whether the strategies used by speakers to differentiate between various speaking conditions are regulated by auditory feedback. Implant users provide a unique opportunity to assess both the effects of long-term absence or degradation of auditory feedback and the consequences of restoring some form of hearing.

There are three dependent variables in the current study:(1) average vowel spacing (AVS), (2) dispersion of vowel tokens around their vowel type mean (in the M1 *vs.* M2 space), and (3) vowel duration. The primary independent variable is speaking condition (clear, normal, or fast). We ask whether there is an influence of auditory feedback on changes in the dependent variables as a function of speaking condition. To address this question, we introduce three additional independent variables: hearing *status* (normal-hearing subjects and postlingually deaf subjects); for implant users, time relative to implantation (pre-implant, one-month postimplant, or one-year postimplant); and for implant users, hearing *state* (presence or absence of auditory feedback, manipulated by switching the implant processor on or off). Table I summarizes the predicted changes in the three dependent variables for each of the four independent variables.

If the phonetic differences associated with changes in speaking condition are influenced by auditory feedback, there will be a significant interaction between speaking condition and one or more of the secondary independent variables related to auditory feedback (hearing status, time relative to implantation, hearing state). This interaction may be observed in any or all of the three dependent variables (AVS, dispersion of vowel tokens, and vowel duration). For example, if AVS is greater for clear speech than for fast speech in normal-hearing subjects but not in implant users, we infer that the poorer audition of implant users prevents them from implementing speaking condition changes in the same way as normal-hearing speakers.

II. METHODS

A. Participants

Thirteen postlingually deafened speakers (five female, eight male) who received cochlear implants (hereafter, cochlear implant users - CI) and ten normal-hearing controls (hereafter, controls - NH) (five female, five male) participated in the study. Table II presents pertinent characteristics of the implant users. The implant was either the Clarion (Advanced Bionics - Buechner *et al.*, 2005), the Combi 40+ (Med-El - Muller *et al.*, 2002) or the Nucleus 24 device, (Cochlear Corp.—Vandali *et al.*, 2000). The implant users were implanted at the Department of Otolaryngology, University of Miami Medical School. As shown in Table II, the group was heterogeneous in several respects. Age at onset of change in hearing varied from 1 to 80 years; age at onset of profound hearing loss ranged from 16 to 80 years. Age at

TABLE II. Characteristics of participants with cochlear implants.

Speaker gender-number	Etiology	PTA unaided thresholds (L-R)	Hearing aid used pre- CI: L, R, both	Implant	Speech strategy	Age at onset of change in hearing	Age at onset of profound loss	Age at cochlear implantation	Years between profound loss and implantation
F_1	Genetic	Aided 55	Right	N24 Contour	ACE	35	59	59	0
M_2	Unknown	109-110	Left	CII Hifocus I	CIS	1	16	33	17
M_3	Unknown	112-110	Right	N24 Contour	ACE	29	56	57	1
F_4	Unknown	100-98	Right	N24 Contour	ACE	7	38	39	1
M_5	Idiopathic	100-102	Left	CII	ACE	1	16	22	6
F_6	Unknown	115-113	Right	N24 Contour	ACE	26	56	57	1
F_7	Genetic	113-106	Left	N24 Contour	ACE	1	24	41	17
M_8	Unknown	110-110	None	N24 Contour	ACE	80	80	81	1
M_9	Noise exposure	Aided bin. 40	Left	N24 Contour	ACE	25	74	75	1
F_10	Unknown	107-110	Right	Combi 40+	CIS	1	26	65	39
M_11	Unknown	85-110	Right	N24 Contour	ACE	50	76	77	1
M_12	Unknown	115-120	Right	Combi 40+	CIS	1	21	46	25
M_13	Surgery	110-110	Right	N24 Contour	ACE	37	37	38	1

cochlear implantation also varied from 22 to 81 years. Normal-hearing controls did not report any speech or hearing anomalies.

B. Procedure

1. Production

The procedure was similar to an earlier study, which was carried out with English and Spanish speakers (Perkell *et al.*, 2001). For the production part of this study, repetitions of the nine American English vowels /*i* ɪ e ɛ a ɑ ʌ o u/ were elicited in random order in a /pVp/ context: "peep, pip, paip, pep, pap, pop, pup, pope, poop." This bilabial consonant context yields minimal lingual coarticulation with the vowel, thus reducing spectral and durational effects of context. Each word was embedded in the following carrier sentence: "Repeat a /pVp/ aboard a bus."[1] (Perkell *et al.*, 2001).

Speakers were asked to produce ten repetitions of the carrier sentence in three speaking conditions: clear, normal, and fast. Normal speech was elicited by asking the subjects to read the utterances aloud at a conversational rate. Fast speech was elicited by asking the subjects to speak as rapidly as possible without eliminating any sounds. Clear speech was elicited by asking the subjects to read the words carefully without increasing loudness (since speaking loudly can introduce spectral changes—Pickett, 1956).

The implant users were first recorded prior to implantation (wearing their hearing aid, if any), one month following implantation, and 1 year postimplant. At the pre-implant stage, subjects read ten repetitions of each utterance, in each of the speaking conditions: normal, fast, clear. At each of the two postimplant time samples (1 month and 1 year), the implant users were recorded in a two-session protocol. Each session contained four blocks of 15 repetitions of each utterance (five in each of the three speaking conditions) in random order for a total of 120 determinations per vowel. Within each block, the order of the three speaking conditions was always the following: normal, fast, clear. During the first session postimplant, the subject read the first and second blocks with the speech processor of the cochlear implant on, the third and fourth blocks with the processor off (hence listening conditions on, on, off, off). The subject kept the processor off for at least 24 h before the second postimplant recording session. During that session, the same protocol was followed, except that the sequence of listening conditions was processor off, off, on, on. To follow up on a previous study conducted in our laboratory (Perkell *et al.*, 2001), this protocol was used in the current study to determine if the magnitude of any observed changes is larger after 24 h of hearing deprivation (by keeping the implant speech processor off) than the magnitude of the changes observed when turning the processor off within a single recording session (Svirsky *et al.*, 1992). Table III shows the arrangement of the utterance materials and processor state in the two time samples postimplantation.

Elicitation utterances were presented to the subjects on a computer monitor. Implant users employed the normal settings of their speech processors for the feedback-on conditions. Participants were seated comfortably in a sound-attenuating room. A head-mounted omnidirectional electret microphone (Audio-Technica, model AT803B) was placed at

TABLE III. Arrangement of recording materials and processor state at 1 month and 1 year following implantation for the implant users.

Time sample	Session	Block 1	Block 2	Block 3	Block 4
One-month	1	On	On	Off	Off
postimplant	2	Off	Off	On	On
One-year	1	On	On	Off	Off
postimpiant	2	Off	Off	On	On

a fixed distance of 20 cm from the speaker's lips. The audio signal was digitized in real time on a computer with a 16 kHz sampling rate.

2. Perception

In order to assess the participants' perceptual abilities, each subject also took a vowel recognition test. Implant users were tested at each of the three time samples (prior to implantation, 1 month and 1 year after implantation), and hearing controls were tested once. The stimuli were /pVp/ syllables, where V was one of the nine American English vowels /*i* ɪ e ɛ a ɑ ʌ o u/. Syllables were recorded by a normal-hearing male speaker and a normal-hearing female speaker at 16 kHz sampling frequency and the signals were amplitude normalized. Female subjects listened to the test with the female speaker and male subjects listened to the test with the male speaker. Stimuli were presented through computer speakers at a comfortable listening level. The task consisted of making a choice among the set of nine American vowels which were also elicited in the production experiment. All nine possible answers appeared as a grid on a touch screen. The participants were instructed to touch the word on the screen that most closely matched what they heard. The sound level was set at a comfortable level for the participants and they were free to adjust the gains on their processors. Stimuli were presented in three blocks and randomized with replacement within each block. Each word was presented at least ten times per block.[2]

C. Data extraction and analysis

The start and end points of each speaker's vowel utterances were labeled automatically based on smoothed rms thresholding exceeding 20% of the peak value for the utterance. For "paip" and "pope," the end point was labeled at the end of the steady state portion of the vowel, before the F1 lowering associated with the offglide. Formant values (F1, F2, and F3) and fundamental frequency values (F0) were extracted algorithmically from an Linear Predictive Coding (LPC) spectrum approximately at mid-vowel using a 40 ms analysis window for F0 and a 25 ms window for the formants. An interactive program developed in MATLAB was used for this analysis.

Formant values were then transformed into mel units (M), a perceptually motivated scale, yielding an M1 by M2 formant plane. Euclidean distances were then calculated between the mean formant frequencies (for each of the 10 repetitions) for all possible pairs of vowels, within each subject. These mean distances were then averaged across subjects to produce a measure of average vowel spacing (AVS—Lane *et al.*, 2001). In order to calculate dispersion values for each vowel type, the Euclidean distance of each token from the mean position of all tokens of that phoneme was determined in the M1 *vs*. M2 space. Those distances were then averaged across repetitions and subjects to obtain the dispersion measure for that vowel. These calculations were completed for each subject, time sample, hearing state, and speaking condition.

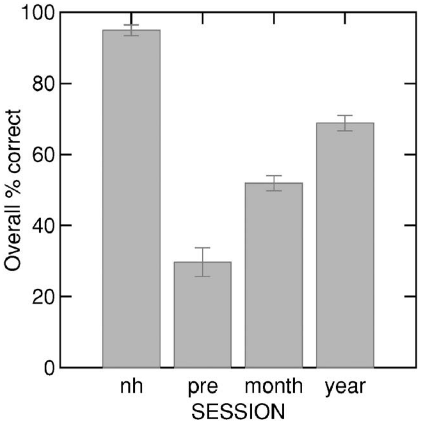

FIG. 2. Percent correct vowel identification, by 13 cochlear implant users in three time samples: prior to activation of their implant speech processors; 1 month postactivation; and 1 year postactivation. Normative data from a group of control subjects with normal hearing are also shown (NH).

III. RESULTS

A. Perception

Results of the vowel recognition test are shown in Fig. 2 for the controls and for the implant users in three time samples (pre-implant;, 1 month, and 1 year postimplantation). For the implant users, a one-way repeated measures analysis of variance (ANOVA) with time sample as a within-subject variable revealed that time sample had a significant effect on the overall percentage correct ($F(2,24)=6.78; p<0.05$). Planned comparisons showed that results increased significantly from the pre-implant stage to 1 month after implantation ($F(1,12)=6.34; p<0.05$) and further improved from this stage to 1 year after implantation ($F(1,12)=5.21; p<0.05$). The use of a cochlear implant thus improved speech perception. However, as shown by a one-way ANOVA contrasting hearing controls and implant users 1 year postimplantation, the implant users' performance at the 1 year postimplant did not reach the nearly perfect score of the controls ($F(1,21)=4.39; p<0.05$).

B. Production

Results are presented separately for the three dependent variables (AVS in the M1 *vs*. M2 space, dispersion around the mean for each type vowel type in that space, and duration). Recall that for each postimplant time sample and hearing state there were two data sets gathered in separate recordings several days apart. There were no significant differences between the two processor-on data sets with respect to each of the three dependent variables (contrast distance: $t=-1.79$, $p>0.05$; dispersion: $t=1.04$, $p>0.05$; duration: $t=-1.80$, $p>0.05$). *T* tests did not reveal any difference between the two processor-off data sets (contrast distance: $t=-1.73$, $p>0.05$; dispersion: $t=2.11$, $p>0.05$; duration: $t=-1.25$; $p>0.05$). Thus, for each time sample and each hearing state, data from the two recording sessions were pooled to provide 60 determinations per vowel, 20 for each of the three speaking conditions.

For each dependent variable (contrast distance, dispersion, and vowel duration) five mixed repeated-measures

TABLE IV. Analysis of variances for ten controls (NH) and 13 implant users (CI) ($*=p<0.05$). Since there were no significant main effects or interactions of the gender variable for any of the dependent variables, this variable is not presented.

(a) Dataset: NH and CI pre-implant

Source	AVS	Dispersion	Duration
Hearing status (NH, CI)	$F(1,19)=9.91^*$	$F(1,19)=0.01$	$F(1,19)=11.14^*$
Speaking condition (clear, normal, fast)	$F(2,38)=33.00^*$	$F(2,38)=0.48$	$F(2,38)=15.40^*$
Hearing status*speaking condition	$F(2,38)=2.15$	$F(2,38)=1.59$	$F(2,38)=1.48$

(b) Dataset: NH and CI 1 year postimplant (with processor on)

Source	AVS	Dispersion	Duration
Hearing status (NH, CI)	$F(1,19)=0.55$	$F(1,19)=9.77^*$	$F(1,19)=11.33^*$
Speaking condition (clear, normal, fast)	$F(2,38)=37.28^*$	$F(2,38)=0.10$	$F(2,38)=13.03^*$
Hearing status*speaking condition	$F(2,38)=1.74$	$F(2,38)=2.07$	$F(2,38)=0.64$

(c) Dataset: CI pre, month, year (processor off)

Source	AVS	Dispersion	Duration
Time sample (pre, 1 month, 1 year)	$F(2,22)=1.51$	$F(2,22)=3.86^*$	$F(2,22)=1.39$
Speaking condition (clear, normal, fast)	$F(2,22)=17.61^*$	$F(2,22)=0.91$	$F(2,22)=11.73^*$
Time sample*speaking condition	$F(4,44)=1.73$	$F(4,44)=1.13$	$F(4,44)=0.40$

(d) Dataset: CI pre, month, year (processor on)

Source	AVS	Dispersion	Duration
Time sample (pre, 1 month 1 year)	$F(2,22)=6.07^*$	$F(2,22)=11.40^*$	$F(2,22)=1.50$
Speaking condition (clear, normal, fast)	$F(2,22)=16.77^*$	$F(2,22)=3.18$	$F(2,22)-11.83^*$
Time sample*speaking condition	$F(4,44)=0.69$	$F(4,44)=0.40$	$F(4,44)=0.71$

(e) Dataset: Cl month and year

Source	AVS	Dispersion	Duration
Time sample (1 month, 1 year)	$F(1,11)=3.11$	$F(1,11)=0.88$	$F(1,11)=1.71$
Speaking condition (clear, normal, fast)	$F(2,22)=19.39^*$	$F(2,22)=1.04$	$F(2,22)=9.77^*$
Hearing state (processor on, off)	$F(1,11)=16.07^*$	$F(1,11)=0.01$	$F(1,11)=0.01$
Time sample*speaking condition	$F(2,22)=1.74$	$F(2,22)=0.05$	$F(2,22)=0.25$
Time sample*hearing state	$F(1,11)=2.50$	$F(1,11)=0.22$	$F(1,11)=0.71$
Speaking condition*hearing state	$F(2,22)=1.73$	$F(2,22)=1.28$	$F(2,22)=1.49$
Time sample*speaking condition*hearing state	$F(2,22)=0.24$	$F(2,22)=1.89$	$F(2,22)=1.00$

ANOVAs were carried out using the following within-subject variables: (1) speaking condition (clear, normal, or fast), (2) for implant users, time sample relative to implantation (pre-implant, 1 month postimplant, or 1 year postimplant), and (3) hearing state (processor on or off). Hearing status (implant users, controls) and speaker gender (female or male) were the between-subject variables. Those ANOVAs correspond to Tables IVa through IVe. There were no significant main effects or interactions of the gender variable for any of the dependent variables. For the sake of clarity, this variable is not presented in the tables.

1. Average vowel spacing (AVS)

Mean AVS values in mels are plotted in Fig. 3, for implant users at each time sample and for each speaking condition (circles=clear; triangles=normal; squares=fast). Filled symbols represent utterances produced by the controls or by implant users with the implant processor on (connected by solid lines). Utterances produced with the processor off (or pre-implant) are shown by unfilled symbols connected by dashed lines. Results of repeated measure ANOVAs are reported in Tables IVa to IVe.

a. Hearing status and speaking condition. As Fig. 3 shows at the left, for controls (NH), the mean AVS value increased by 29 mels from the fast (squares) to the normal condition (triangle) and 26 mels from normal to clear (circle). A similar effect of speaking condition was observed for implant users at the pre-implant stage (pre). Table IVa reports the outcome of an ANOVA based on production measures for the controls and those for the implant users pre-implant. The table shows there was a significant effect of speaking condition on AVS. Planned comparisons of that effect showed that AVS was significantly greater in clear than in normal speech ($F(1,19)=17.36; p<0.05$), and was significantly greater in normal than in fast speech ($F(1,19)=41.81; p<0.05$). Figure 3 also shows that implant users at the pre-implant stage and hearing controls varied AVS similarly in response to changes in speaking conditions, confirmed by the lack of a significant interaction between hear-

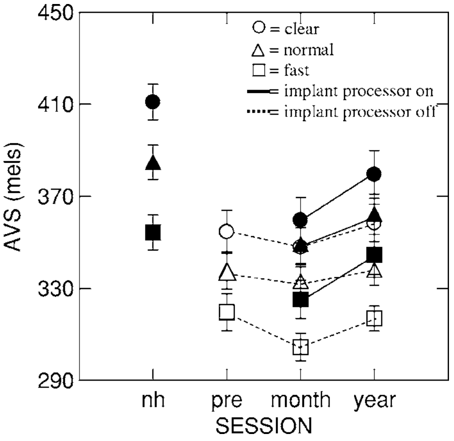

FIG. 3. Mean values of average vowel space (AVS) for control subjects (NH) and implant users in three speaking conditions (clear, normal, fast). For the latter group, data are shown at three time samples: prior to implantation (pre), 1 month (month) and 1 year (year) after implantation. Solid line: implant processor on; dotted line: implant processor off. Error bars are 0.5 standard error of the mean.

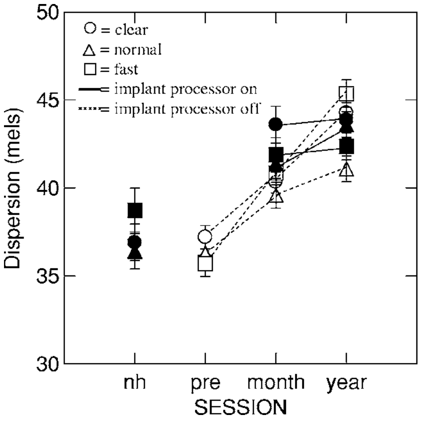

FIG. 4. Mean values of token dispersion in the M1 *vs.* M2 plane for the nine vowels elicited for controls (NH) and implant users in three speaking conditions (clear, normal, fast). Data for the implant users are presented at three time samples: prior to implantation (pre), 1 month (month) and 1 year (year) after implantation. Solid line: implant processor on; dotted line: implant processor off. Error bars are 0.5 standard error of the mean.

ing status and speaking condition (Table IVa).

When comparing hearing controls and implant users after 1 year of implant use in the processor on condition, it can be observed in Fig. 3 that both groups varied average vowel spacing with speaking condition to approximately the same extent. Table IVb shows that this effect was significant, and that there was no significant interaction between speaking condition and hearing status.

Pooling across speaking conditions, average vowel spacing produced by implant users at the pre-implant stage was significantly smaller than produced by hearing controls (significant effect of hearing status in Table IVa). Even though it appears in Fig. 3 that the controls' AVS values are higher than the implant users' with processor on at 1 year postimplant, this difference was not significant (Table IVb).

b. Time sample and speaking condition. Inspection of Fig. 3 suggests that among the implant users, the differences between AVS in clear, normal, and fast speaking conditions did not change with implant use from the pre-implant stage to 1 month and 1 year postimplantation for the processor off condition. This finding is confirmed in Table IVc by the presence of a significant effect of speaking condition on AVS with processor off, but the lack of a significant interaction between speaking condition and time sample.

Figure 3 and Table IVd show that no significant interaction was found between speaking condition and time sample in the processor on condition. Thus, in the three time samples with their evolving enhancement of perceptual accuracy and contrast distance, the effects of speaking condition remained comparable. When averaging across speaking conditions, AVS values increased with implant use: planned comparisons tests revealed that implant users' mean AVS did not change from pre-implant (no processor) to 1 month postimplant with processor on; however, values at 1 year postimplant with processor on were significantly higher than values at pre-implant ($F(1,11)=13.36; p<0.05$) and values at 1 month postimplant ($F(1,11)=10.38; p<0.05$). Hence, the use of an implant increased contrast distance, but only from 1 month to 1 year after implantation.

c. Hearing state and speaking condition. Figure 3 shows that AVS values were larger in the processor on condition (solid line) than in the processor off condition (dotted line), also demonstrated by a significant effect of hearing state in Table IVe. This difference in AVS between the two hearing-state conditions is observed both at 1 month and 1 year postimplant, as confirmed by the lack of a significant interaction between hearing state and time sample (Table IVe).

Temporarily depriving the speaker of auditory feedback by turning the implant processor off did not change the extent to which implant users increased contrast distances when changing from fast to normal to clear speaking conditions. As can be seen in Table IVe, speaking condition had a significant effect on AVS values for implant users (pooling across hearing state) but the interaction between hearing state and speaking condition was not significant.

To summarize, averaging across speaking conditions, implant users pre-implant had smaller values of average vowel spacing than controls. After 1 year of implant use, in the processor on condition, implant users' AVS values overlapped with those found for controls. Temporarily depriving the implant user of auditory feedback after implantation yielded a significant decrease of values of AVS, compared to the condition where auditory feedback was provided by the implant. However, this manipulation of auditory feedback did not affect the differences in AVS between speaking conditions. Thus the effects of speaking condition are similar for both groups, at all time samples and for both hearing states.

2. Dispersion

The effects of speaking condition, time sample, and hearing state on dispersion values are shown in Fig. 4. All values are in mels. Results of repeated measures ANOVAs are reported in Tables IVa–IVe in the Dispersion column.

a. Hearing status and speaking condition. As Fig. 4 indicates, dispersion values did not differ significantly with changes in speaking condition, pooled over hearing status with pre-implant measures for the implant users (Table IVa). The same was true if the 1 year postimplant measures were used instead (Table IVb). There were no significant interactions between hearing status and speaking condition.

When averaging across speaking conditions, it can be observed from Fig. 4 that the dispersion values for the implant users at the pre-implant stage did not differ reliably from those of controls (no significant effect of hearing status in Table IVa). However, values at 1 year postimplant with processor on were significantly higher than those of normal-hearing speakers (significant effect of hearing status in Table IVb).

b. Time sample and speaking condition. Inspection of Fig. 4 suggests that the use of the implant did not induce implant users to vary dispersion values according to speaking condition. No significant interaction of time sample and speaking condition was found in the processor off condition (Table IVc) or the processor-on condition (Table IVd). There was, however, a significant effect of time sample on dispersion for each processor state (pooling over speaking condition). With processor off, planned comparisons showed that dispersion values at 1 month postimplant were significantly higher than at the pre-implant stage ($F(1,11)=5.33; p < 0.05$), but were not significantly different at 1 year from dispersion values measured at 1 month after implantation. Planned comparisons also revealed that dispersion values increased significantly (by about 5 mels) from pre-implant to 1 month postimplant in the processor on condition ($F(1,11) = 4.32; p < 0.05$). However, dispersion values at 1 year postimplantation did not significantly differ from those measured at 1 month postimplantation (mean value of 41 mels).

c. Hearing state and speaking condition. Among implant users, dispersion values did not vary from fast to normal to clear speech condition, regardless of whether feedback was supplied or not in the 1 month and 1 year recording sessions. As observed in Table IVe, the interaction between time sample, hearing state, and speaking condition was not significant.

To summarize, when pooling across speaking conditions, dispersion values for implant users at the pre-implant stage were similar to those of controls but values 1 year postimplant with processor on were higher than those of controls. Implant users' overall mean dispersion values increased significantly from pre-implant to 1 month postimplant, but didn't change significantly thereafter. No difference in dispersion values according to speaking condition was found for either of the speaker groups. Thus, at all three time samples, when changing from fast to normal to clear speech conditions, implant users did not produce vowels that were more tightly clustered within vowel categories.

3. Duration

Figure 5 gives the variation of vowel duration according to speaking condition, hearing state, and time sample for implant users. Mean values for controls are also shown. Results of repeated measures ANOVAs are reported-in Tables IVa–IVe in the right-most column.

a. Hearing status and speaking condition. An examination of Fig. 5 reveals that controls and implant users at the pre-implant stage increased vowel duration when changing from fast to normal to clear speech conditions. Indeed, a significant effect of speaking condition was found (Table IVa). Planned comparisons showed that vowels were significantly shorter (by about 50 ms) in fast speech than in normal speech ($F(1,19)=20.29; p < 0.05$), and vowels were significantly longer (by about 18 ms) in clear speech than in normal speech ($F(1,19)=5.35; p < 0.05$). When comparing controls and implant users at 1 year postimplant (processor on condition), a similar pattern was found (significant effect of speaking condition in Table IVb). It is worth noting that both speaker groups varied duration values to the same extent (no significant effect of interaction between speaking condition and hearing status in Tables IVa and IVb).

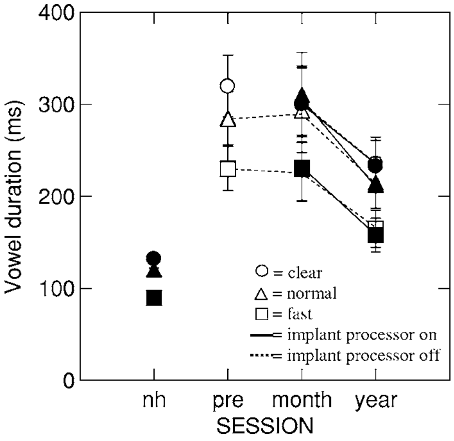

FIG. 5. Mean values of vowel duration for controls (NH) and implant users in three speaking conditions (clear, normal, fast). For the latter group, data are shown at three time samples: prior to implantation (pre), 1 month (month) and 1 year (year) after implantation. Solid line: implant processor on; dotted line: implant processor off. Error bars are 0.5 standard error of the mean.

When averaging across speaking conditions, it can be observed that implant users produced longer vowels (mean duration ~280 ms) than controls (mean duration of 114 ms) (significant effect of hearing status, Table IVa). Even after 1 year of implant use, in the processor on condition, implant users' vowels remained longer (mean duration of 205 ms) than those found for controls (significant effect of hearing status, Table IVb).

b. Time sample and speaking condition. As can be seen in Fig. 5, no interaction of time sample and speaking condition was found among the implant users in the processor off condition (Table IVc). The same was true for a comparison of duration measures at the pre-implant stage and at the postimplant stages in the processor on condition (Table IVd). Thus, duration of implant use did not change the extent to which postlingually deaf speakers changed vowel duration across speaking conditions.

Figure 5 shows that duration tends to be reduced in the direction of normative values from 1 month to 1 year postimplant; however, this effect of time sample was not significant. Furthermore, duration did not significantly decrease from the pre-implant stage to 1 year after implantation, neither in the processor off condition (Table IVc) nor in the processor on condition (Table IVd).

c. Hearing state and speaking condition. The interaction of hearing state (processor on or off) and speaking condition in determining vowel duration was not significant (Table IVe), leading to the inference that the maintenance of durational differences between clear, normal, and fast speech did not depend on whether or not auditory feedback was supplied by the implant processor.

To summarize, long-term deprivation of auditory feedback induced implant users to produce longer vowels than controls, but there were no differences in vowel duration related to the interaction of speaking condition and hearing state in either group.

IV. DISCUSSION

A. Evaluating the role of auditory feedback

The results of this study show that postlingually deafened adults, instructed to speak under three different speaking conditions, varied contrast distances and vowel duration, but not dispersion. The section on objectives stated that if the phonetic differences associated with changes in speaking condition were influenced by auditory feedback, there would be a significant interaction between speaking condition and one or more of the independent variables related to auditory feedback (hearing status, time relative to implantation, hearing state) in determining changes in average vowel spacing, dispersion of vowel tokens, and vowel duration. As discussed below, no such interactions were found.

1. Average vowel spacing (overall vowel contrast)

There was a significant effect of speaking condition on overall vowel contrast. Figure 3 shows that for both groups based on hearing status (implant users and controls), AVS in clear speech was larger than in normal speech, which was larger than in fast speech. However, no significant interaction was found between speaking condition and hearing status or hearing state or time relative to implantation. These results lead to the inference that the maintenance of spectral distinctions between speaking conditions was not altered by profound hearing loss, which had lasted at least a year for all but one of the implant users. Consistent with the conclusion that auditory feedback did not influence changes in contrast due to speaking condition, the differences in contrast distances between clear, normal, and fast speech did not change from pre-implant to 1 month postimplant, nor from 1 month postimplant to 1 year postimplant, whether or not auditory feedback was supplied by the implant processor (Fig. 3). The absence of a significant interaction between speaking condition and the other independent variables does not by itself confirm that there were no such interactions but it is worth noting significant main effects were found for hearing status, speaking condition, and time sample (with processor on). The corresponding caveat applies to the other dependent variables, discussed below.

2. Dispersion

Regarding the dispersion of vowel tokens around their mean positions in the formant plane, an interaction between speaking condition and auditory feedback would have suggested that the differences in dispersion among speaking conditions are regulated by auditory feedback. As shown in Fig. 4, implant users at the pre-implant stage did not vary dispersion values significantly when changing from fast to normal to clear speech condition. No interaction effect of time sample and speaking condition was found in the processor on condition or the processor off condition. Since there was no change in the effect of speaking condition on dispersion despite a year's use of the implant, there was no evidence that auditory feedback plays a role in regulating the differences in dispersion values among speaking conditions.

For hearing controls, token dispersion around the mean did not differ significantly according to speaking condition. This pattern contrasts with previously published studies on the effects of speaking conditions on dispersion values, where it was found that when instructed to speak clearly, speakers produced tighter clustering of vowel tokens around the mean (cf., Picheny *et al.*, 1986). This disparity in results may be attributable to differences between experimental paradigms. For example, in the study of Picheny *et al.*, speakers read nonsense sentences with embedded real words. Phonemic and prosodic contexts varied from one sentence to the next. In the present study, target vowels were elicited in the same phonemic environment and prosodic context across repetitions (/pVp/). There were also differences between the methods for eliciting clear speech. In Picheny *et al.* (1986), feedback was provided to the speaker during the recording to reinforce the clear speech instruction; in the current study, the speaking conditions were elicited only by instructions to the subjects.

3. Duration

If duration measures had yielded a significant interaction effect between any of the independent variables related to auditory feedback (hearing status, time sample, hearing state) and speaking condition, that would lead to the inference that auditory feedback regulates the durational contrasts between speaking conditions. It was found that the differences in vowel duration between clear, normal, and fast conditions for implant users were in the range of those found for controls, at all time samples and in both hearing states. No interaction of speaking condition with hearing status or time sample was found. Thus, the maintenance of durational contrasts among speaking conditions was not influenced by sustained auditory deprivation or the subsequent provision of auditory feedback.

Recall that vowels produced in the clear speech condition were longer than those produced in the normal condition. When averaging across speaking conditions, it was found that implant users at the pre-implant stage produced significantly longer vowels than controls (280 ms compared to 114 ms). Even after 1 year of implant use, vowels remained longer than normative values found for controls.

B. Interpreting the results in the light of the DIVA model

Our results can be interpreted in the light of the DIVA model, described earlier and represented in Fig. 1.

1. Contrast distances

In the present study, the observation that vowel contrast distances (measured by AVS) in deaf speakers prior to implantation were lower than hearing controls, is compatible with the idea that feedforward commands had been degraded by auditory deprivation. Average vowel spacing remained unchanged from the pre-implant stage to 1 month postimplantation. AVS increased from 1 month to 1 year postimplant in the processor-on condition, but remained unchanged in the processor-off condition. This pattern is in line with the behavior of the DIVA model. DIVA predicts that speakers with cochlear implants will first use the new auditory feedback provided by the implant to recalibrate their feedback control subsystem. Until the feedback control system has been recalibrated, feedforward commands cannot be recalibrated since their tuning relies on a well-tuned feedback control system. The use of the newly acquired auditory feedback may even be detrimental to the speech of implant users shortly after implantation because the auditory feedback provided by the implant is very different from the feedback provided by the auditory system before the onset of deafness. As a result, the implant recipient's feedback control system will be improperly tuned initially, leading to somewhat degraded speech when auditory feedback is available, which in turn may degrade feedforward commands. This pattern has been reported earlier (Lane *et al.*, 2005). After implantation, according to the model, the newly acquired auditory feedback is recalibrated increasingly with time, and only after it is properly tuned will it start improving the feedforward commands. These processes may require some time, and the 1 year postimplantation stage has been chosen here to represent a reasonable extended period of implant use after which implant users may have recalibrated their feedforward commands. Our results, as others (Lane *et al.*, 2006) suggest that, although this retuning of the feedforward command has typically begun before 1 year after implantation, it is not complete by 1 year.

The strategies for changing contrast distance with speaking condition were not mediated by auditory feedback in this experiment. We reach this conclusion because implant users as well as controls increased contrast distance from normal to clear speaking condition by similar amounts and there was no evidence of an effect of processor state nor of the length of time the speaker had been using the implant. Taken together, those results suggest that long-term deprivation of auditory feedback (as in postlingually deaf speakers) results in a deterioration of contrast distances for among vowel categories of a language, but the ability to enhance contrast distance when given instructions to vary speaking condition is not affected. Since the implant users in the present study are *postlingually* deafened, they had long-term auditory experience during which their feedback system was used to calibrate their feedforward commands. During the sustained auditory deprivation of profound deafness, their feedforward command systems could not have been maintained by the auditory feedback system. However, these speakers still have residual feedforward commands that were acquired when they could hear and they have intact somatosensory feedback. In this condition, deaf speakers may rely on their own knowledge of speech motor control encoded in the feedforward commands to implement variations required for different speaking conditions (for example, greater or lesser separation between contrasting vowels).

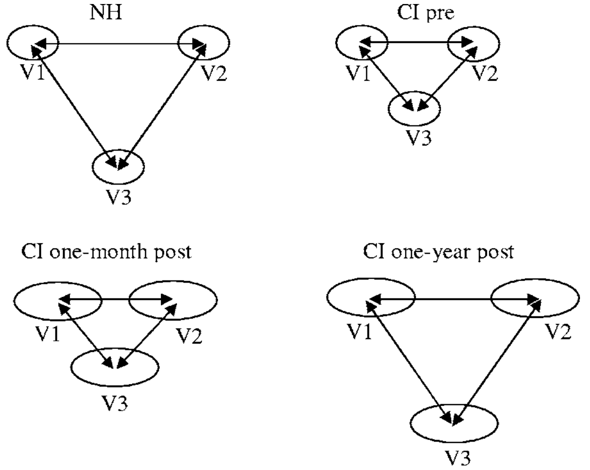

FIG. 6. Schematic representations of the results for contrast distance and vowel dispersion in the present study for controls (upper left panel) and implant users at three time samples: pre-implant (upper right panel), 1 month postimplant with processor on (lower left panel) and 1 year postimplant with processor on (lower right panel). For the sake of clarity, only three vowels (V1, V2, V3) are represented. The size of the ellipses associated with the vowels represents dispersion, and the size of the double-headed arrows corresponds to the magnitude of contrast distance.

2. Dispersion

With respect to the dispersion of vowel tokens around their mean in the formant plane, our results show a somewhat different pattern from that obtained with contrast distance. Figure 6 schematizes the results obtained for contrast distance and vowel dispersion, for controls and implant users at the three time samples, in the processor on condition for the postimplant stages. For the sake of clarity, only three vowels are represented (V1, V2, V3). Vowel dispersion, related to the size of the goal region for each vowel category, is denoted by the size of the ellipses associated with the vowels. The length of the double-headed arrows represents the magnitude of contrast distance between pairs of vowels. Data from the present study reveal that even after long-term auditory deprivation, implant users at the pre-implant stage produced dispersion values that were still in the range of those found for controls, whereas contrast distance had significantly decreased (compare the left and right upper panels with one another in Fig. 6). Thus, the lack of auditory feedback affected the control of contrast distance but goal region size, measured by the value of vowel dispersion, remained unaffected.

One month after implantation, the use of auditory feedback provided by the implant resulted in an increase in dispersion, and no significant change in contrast distance (compare the upper right panel and the lower left panel in Fig. 6). The increase in dispersion with the use of an implant is consistent with the DIVA model since it reflects the fact that the auditory feedback system is poorly tuned, thus leading to an additional degradation of speech production shortly after implantation (i.e., the speaker's poorly tuned auditory feedback control system actually degrades, rather than improves, speech). This may be attributable to the very different nature of the auditory feedback provided by the prosthetic device, compared to the feedback available when the speaker was still hearing. It is also predicted by DIVA that the low resolution of the implant will lead to a larger target region (dispersion): the implant recipients cannot hear some subtle differences that distinguish poor from good exemplars of a phoneme category, thus they include some relatively poor exemplars in their production target regions, yielding greater dispersion. Consistent with this account, prior research has shown a relation between contrast distance and acuity, leading to the inference that speakers with greater acuity have smaller target regions for vowel production (Villacorta *et al.*, 2005; Perkell *et al.*, 2004a, b). Contrast distance values and dispersion values can thus follow different time courses from pre-implant to 1 year postimplantation.

It is, however, worth noting that in the present study, implant users increased dispersion values (pooling across feedback conditions and speaking conditions) from the pre-implant stage to 1 month postimplant, whereas a different pattern was observed in a bite-block study conducted in our laboratory on a different group of implant users (Lane *et al.*, 2005). In the latter study, mean token dispersion measured without bite blocks dropped significantly from the pre-implant stage (around 55 Hz) to the 1 month postimplant stage (around 45 Hz). In another difference between the two studies, the current one found implant users' dispersion values were not higher at the pre-implant stage than the normal controls' (mean value of 37 mels), whereas in Lane *et al.* (2005) dispersion values at the pre-implant stage were higher than those of hearing control subjects. The differences between these two sets of results may be due in part to differences in subject populations, dialect regions, and elicitation procedures. Subjects recorded in the present study were from the Miami area, a different dialectal region compared to the study of Lane *et al.*, in which subjects were recruited in the Boston area. Furthermore, in the present study, values were averaged over nine vowels in /pVp/ contexts embedded in a carrier phrase whereas in Lane *et al.* (2005), dispersion values were calculated over five vowels in carefully pronounced isolated words ("heed," "hid," "head," "had," and "hot"). We do not have an explanation at this time that links those methodological differences to the disparity between the two sets of results.

In the current study, we infer that the implant users, after 1 year of implant use, had time to successfully retune their auditory feedback systems, following which the system was used to recalibrate the feedforward control commands effectively. As a result, contrast distances increased at 1 year postimplant compared to 1 month postimplant (compare lower panels in Fig. 6), but dispersion values remained unchanged. The low resolution of the implant no doubt contributed to the larger target region (dispersion) at 1 year postimplant relative to controls. It is unlikely that further improvements in the feedforward commands will be able to reduce this resolution-related portion of the overall variability seen at 1 year postimplant unless there is some improvement in implant users' perceptual acuity that might result from improved signal processing.

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[1] This carrier phrase was chosen to make it prosodically as compatible as possible with a phrase spoken by Spanish-speaking participants (data not reported here), "Repita/pVp ə/ por favor."

[2] Due to a technical problem with the stimulus presentation software, the exact number of repetitions of each syllable varied from 27 to 34 depending on the speaker.

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