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The development of speech adaptation to an artificial palate

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An investigation of adaptation to palatal modification in [s] production was conducted using acoustic and perceptual analyses. The experiment assessed whether adaptation would occur subsequent to a brief period of intensive, target-specific practice. Productions of [sa] were elicited at five time intervals, 15 min apart, with an artificial palate in place. Between measurement intervals, subjects read [s]-laden passages to promote adaptation. Results revealed improvement in both acoustic and perceptual measures at the final time interval relative to the initial measurement period. Interestingly, the data also suggested changes to normal (unperturbed) articulation patterns during the same interval. Results are discussed in relation to the development of speech adaptation to a structural modification of the oral cavity. © *1997 Acoustical Society of America.*
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INTRODUCTION

A fundamental question, and one that has dominated much of the experimental inquiry into speech production, is to what extent, if any, sensory feedback interacts with central control signals in the control and coordination of speech movements (McFarland and Lund, 1995; Smith, 1992). Observing speech compensation to dynamic and static oral-articulatory perturbations has provided valuable insights into the potential role of sensory feedback in the control of speech gestures. Numerous investigations have demonstrated that speakers are able to relatively easily and rapidly adapt to many perturbations to the articulatory system (e.g., Abbs, 1986; Kelso and Tuller, 1983; Lindblom *et al.*, 1979; Warren *et al.*, 1980, 1984), suggesting predictive processes of speech motor programming. Nonetheless, more recent data suggest that compensation depends to some extent on the nature of the perturbation, the specific speech sounds targeted, and individual articulatory strategies adopted by speakers (Flege *et al.*, 1988; McFarland and Baum, 1995; Munhall *et al.*, 1994; Savariaux *et al.*, 1995).

Further, and in contrast to much of the data on perturbations that inhibit specific movements [e.g., fixation of the mandible by a bite block or application of a load to the lower lip (Gay *et al.*, 1981; Kelso and Tuller, 1983; Lindblom *et al.*, 1979; Lubker, 1979; but cf. Baum *et al.*, 1996; Flege *et al.*, 1988; Fowler and Turvey, 1980; McFarland and Baum, 1995)], a great deal of data have shown that compensation for a structural change to the oral environment (e.g., an artificial palate) may require a much more lengthy period of adaptation (Hamlet, 1973; Hamlet and Stone, 1974, 1978; Hamlet *et al.*, 1979). The presence of an artificial palate in the mouth has been found to result in increased duration of the sibilant consonants and an increased number of articulatory errors, particularly as palatal thickness increases (Hamlet, 1973; Hamlet and Stone, 1974, 1978; Hamlet *et al.*, 1979). The sibilants tend to be most affected due to the apparent requirement of a precise positioning of the tongue relative to the palatal surface for their accurate production (Flege *et al.*, 1988).

In a previous experiment, McFarland *et al.* (1996) reported significant changes in fricative ([sʃ]) spectra with and without an artificial palate in place. The palates were found to be particularly perturbing to [s] articulation due to increased thickness at the alveolar ridge. Even after a 15-min period of conversation with the palate in place, spectral energy concentrations for [s] were significantly lower than under normal conditions. In addition, the differences were found to be perceptually salient to a group of naive listeners.

Studies have shown that speech gradually improves following the insertion of an artificial palate (Hamlet and Stone, 1976a, b; Hamlet *et al.*, 1978; Hamlet and Stone, 1978) but that normal speech may not be re-acquired for several days or weeks. The period of progressive improvement may reflect the development of new articulatory patterns to accommodate the structural change (McFarland *et al.*, 1996). It is of particular interest to determine the factors which contribute to the development of these new articulatory routines and the role that various types of sensory feedback may play in such adaptation. For example, many studies have suggested that sensory feedback (particularly auditory feedback) is very important in the development of speech motor control (Borden, 1979; Osberger and McGarr, 1982; Smith, 1992) but its role in mature speech production is less clear (e.g., Matthies *et al.*, 1994, 1996; Perkell *et al.*, 1992; Waldstein, 1990). By perturbing the articulatory system in certain specific ways, we can observe the response and requirements of a mature system in the development of novel articulatory movements.

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TABLE I. Characteristics of the palate for each subject.

Subject	Shape of palate	Width of palate (at molars) (mm)	Length of palate (at molars) (mm)	Depth of palate (at molars) (mm)	Width of anterior palate (at cuspids) (mm)	Length of anterior palate (at cuspids) (mm)	Depth of anterior palate (at cuspids) (mm)
1	slightly V	43	36	17	32	13	7
2	V shaped	48	36	21	33	12.5	11.5
3	U shaped	46	38	19	32.5	14	11
4	U shaped	46	37	20	33	16	13.5
5	V shaped	45	40	20	32	14.5	14
6	U shaped	46.5	37	17	33.5	12	10
7	Slightly V	45	37	18	31.5	12	15

In so doing, we may identify the factors which are critical to successful adaptation, as well as those which impede compensation. We may also be able to determine whether adaptation can, by some means, be facilitated, perhaps by increasing the intensity of practice or adjusting the feedback provided.

In order to experimentally investigate the adaptation period in otherwise normal speakers, it is necessary to first determine whether the time required can be reduced to a period manageable in the laboratory. In previous studies that have examined compensation over time, observations of speech production were recorded longitudinally (e.g., over a period of several days or weeks (Hamlet, 1973; Hamlet and Stone, 1974, 1978; Hamlet *et al.*, 1979), but there were no controls on the speech activity during those intervals. Each individual subject may thus have had varying amounts of practice with the artificial palate in place, with varying degrees of target sound production even during similar time frames.

Our goal in the present investigation was to examine the adaptation process in order to facilitate the understanding of fundamental mechanisms involved and to ultimately explore the role of sensory feedback in speech adaptation. As a preliminary step, then, we sought to ascertain whether adaptation would occur subsequent to intensive, target-specific practice. If adaptation occurs within a relatively brief period (relative to the lengthy period reported in previous investigations; Hamlet, 1973; Hamlet and Stone, 1974, 1978; Hamlet *et al.*, 1979), various types of feedback can be systematically modified or eliminated in order to determine their role in articulatory compensation to a structural modification.

The objective of the present investigation was, therefore, to examine speakers' ability to compensate for the insertion of an artificial palate with a thicker than normal alveolar region in [s] production, over a relatively brief period of time, given intensive, focused practice. Both acoustic and perceptual analyses were utilized to determine whether a 1-h period of [s] practice would allow speakers to modify their established articulatory programs in order to compensate for the presence of an artificial palate to produce perceptually and acoustically adequate [s] tokens.

I. METHODS

A. Acoustic analyses

1. Subjects

The subjects included seven adult female native speakers of (Québec) French, with a mean age of 23 years. Six of the subjects (with the exception of S7) had participated in a previous study of compensation to palatal modification (McFarland *et al.*, 1996).[1] All subjects were free from current or prior history of speech, language, and hearing deficits. Measurements of palate width, depth, and length from specified landmarks were calculated from dental impressions made for each individual. These values are displayed in Table I.

2. Stimuli and procedures

An artificial palate was constructed for each subject from dental acrylic. The palate was fabricated such that a 6-mm ridge extruded near the alveolar ridge, at the midline of the cuspid-to-cuspid plane from the incisive papilla to 2 mm posterior to the cuspids, in order to perturb normal [s] production. The palate tapered to 1 mm posterior to that plane and was fitted with ball clasps to hold it in place. Figure 1 illustrates the palatal configuration in mid-sagittal (a) and inferior (b) views. (For six of the subjects, the palate had been made for a previous experiment.) The target stimulus, [sa], was elicited 30 times at each of five time intervals, 15 min apart, with the palate in place—that is, at 0, 15, 30, 45, and 60 min. In addition, at time 0 (prior to any practice) and time 60 (after 60 min of practice), 30 repetitions of [sa] were elicited under normal conditions (i.e., with no artificial palate). At these two test intervals, three blocks of ten tokens were produced alternately in the normal and perturbed conditions, beginning with the normal condition. That is, ten normal tokens were followed by ten tokens with the palate in place, and so on. At all other times during the 60-min interval the palate was in place; speakers were instructed to produce normal [s] but were given no specific instructions regarding maximizing the quality of their productions.

Stimuli were presented in orthographic form on a computer screen every 5 s and subjects were instructed to read each stimulus as it appeared. The palate was removed and inserted by the subject as necessary. Between time intervals, subjects were required to read aloud passages specially constructed to be heavily laden with [s] for 15 min in order to

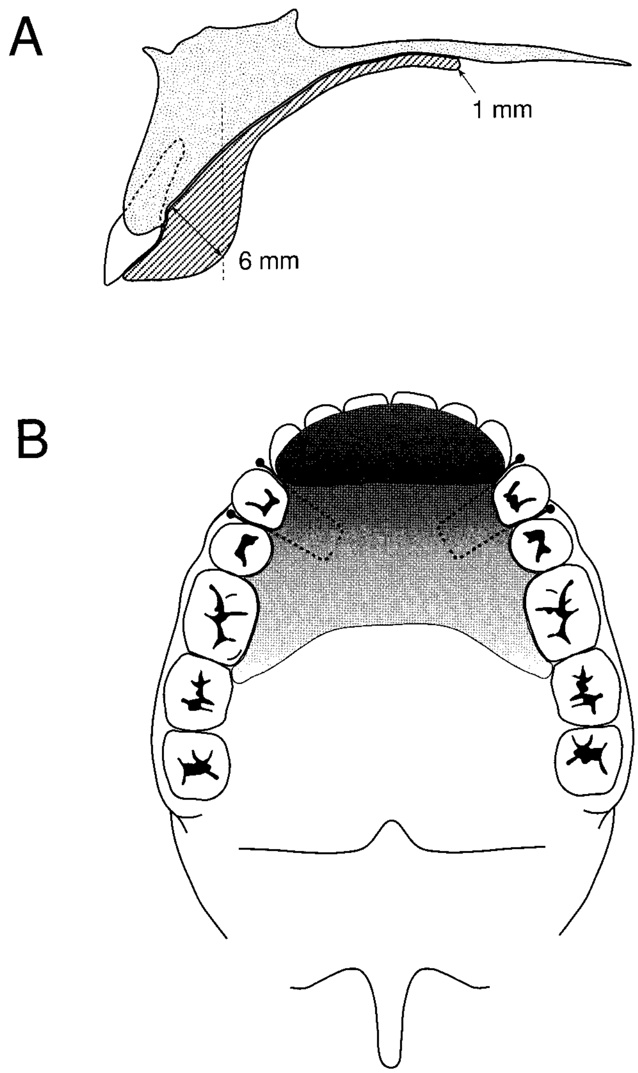

FIG. 1. Artificial palate configuration in mid-sagittal (a) and inferior (b) views. The vertical dotted line in (a) indicates the point at which (distal to the cuspids) the appliance begins to taper to 1-mm thickness.

promote adaptation to the perturbation. On average, during each 15 min interval, each subject produced 665 [s] tokens in a variety of phonetic environments, for an average total of 2660 productions. Recordings of the target utterances were made in a sound-treated room using a Sony DTC-57ES digital tape recorder and head-mounted directional microphone (AKG-HD421U) to ensure a constant distance from the microphone to the speaker's mouth.

3. Analyses

The 30 [sa] productions at each time interval with the palate in place, as well as the 30 repetitions produced under normal conditions at time 0 and time 60 were digitized at a rate of 20k samples/s with 12-bit quantization and a 9-kHz low-pass filter, using the BLISS speech analysis system (Mertus, 1989). A 20-ms full Hamming window was placed at the midpoint of each fricative and a centroid frequency was computed from Fourier analysis. The centroid is the first moment of the spectral distribution and represents a weighted average of the spectral peak frequencies. It has been used previously to characterize the quality of fricative production and as an indicator of degree of adaptation to articulatory perturbation (Forrest *et al.*, 1988; McFarland and Baum, 1995; McFarland *et al.*, 1996). Although spectral moments may not reliably serve to singularly differentiate fricatives from one another (Shadle and Mair, 1997), under normal conditions with a constant frequency range and vowel environment, the centroid (or first spectral moment) remains relatively stable for a given fricative (Shadle and Mair, 1997) and may reflect, in part, the point of constriction within the vocal tract. We thus chose to concentrate our analyses on the centroid frequency (first spectral moment) as a reflection of the accuracy of [s] production.

B. Perceptual analyses

1. Subjects

The listeners in this experiment were ten native (Québec) French-speaking adults with training in speech-language pathology who were familiar with assessments of articulatory quality. None of the listeners had participated as a speaker in experiment 1.

2. Stimuli

From the recorded stimuli of experiment 1, those productions elicited at time 0 and time 60 in both the palate and normal conditions were utilized in the perception test. Five randomly selected tokens for each of seven speakers in each palate condition were included, for a total of 140 [sa] stimuli presented in random order. In addition, ten ''high-quality'' exemplars and ten ''poor'' exemplars were presented to listeners prior to the experimental stimuli as a training set. These stimuli had been selected by the experimenters based on their acoustic and perceptual attributes. The ''poor'' exemplars were those whose centroid frequencies were furthest from the normal (unperturbed) mean; the ''high-quality'' exemplars were all taken from the set of normal productions (at time 0), based on perceptual judgments by the experimenters.

3. Procedure

Auditory stimuli were presented to listeners individually over headphones (Sony MDR 7506) in a sound-treated room, along with a visual analogue scale of 10 cm in length, with the endpoints marked as ''unintelligible'' and ''perfect.'' There was a 5-s interstimulus interval for the rating and subjects were given a short break at the midpoint of the experiment. Listeners were instructed to rate the quality of each production (concentrating solely on the fricative [s]), based on the training samples and their clinical experience, by making a mark at an appropriate point along the 10-cm scale.

II. RESULTS

A. Acoustic analyses

Mean centroid frequencies were calculated at each time interval for the normal and palate conditions separately. (The normal conditions only appeared at time 0 and time 60.) These data are displayed in Fig. 2, collapsed across subjects.

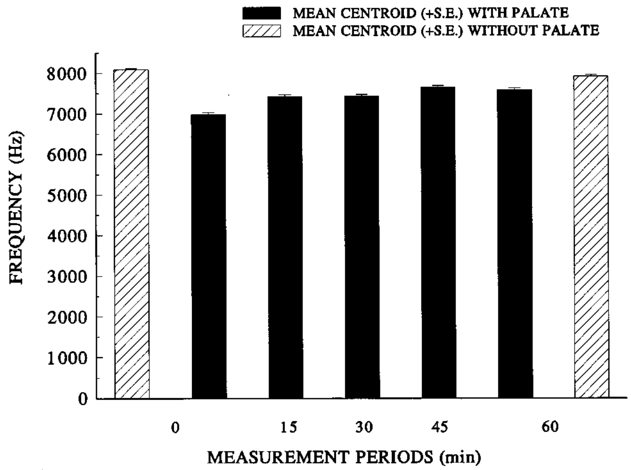

FIG. 2. Mean centroid frequencies (+s.e.) at each time interval for the normal and palate conditions. (The normal conditions only appeared at time 0 and time 60.)

A one-way analysis of variance (ANOVA) comparing centroids in the five palate conditions revealed a main effect for test interval [$F(4,24)=14.87$, $p<0.001$]. Multiple comparisons across intervals demonstrated significant differences between time 0 and all other intervals; in addition, time 15 and time 30 differed significantly from time 45. The improvement in compensation at the later time intervals (i.e., at time 60 relative to time 0) was shown by each individual subject, as may be seen in Table II which displays the centroid values for each subject at the five test intervals. Although one might have expected a reduction in variance across intervals, as shown in Table II, no consistent pattern emerged across subjects' standard error values.

ANOVAs were also conducted to assess the effect of the palatal perturbation at time 0 and time 60. A test interval×palate condition ANOVA revealed significant main effects of test interval [$F(1,6)=6.12$, $p<0.05$] and palate condition [$F(1,6)=65.61$, $p<0.001$], and a significant test interval×palate condition interaction [$F(1,6)=79.94$, $p<0.001$]. Simple effects analyses showed a significant effect of the palate at time 0 [$F(1,6)=141.97$, $p<0.001$], with centroids in the palate condition lower than those in the normal condition (an average difference of 1102 Hz). At time 60, there was still a significant difference between centroids in the normal and palate conditions [$F(1,6)=11.63$, $p<0.02$], but the magnitude of the difference was much smaller (an average of 329 Hz). Three subjects (S2, S6, S7) displayed the smallest differences between conditions at time 60. An examination of the palatal characteristics of these three individuals revealed no apparent structural explanation for their better performance (see Table I). It is interesting to note that S7 was the one subject who had not had any previous experience with the palate in place and performed similarly to several other subjects.

Finally, a comparison of the normal conditions at time 0 and time 60 was undertaken. Somewhat surprisingly, a significant main effect of test interval was found [$F(1,6)=5.85$, $p<0.05$]. However, the difference in average centroid frequency at the two intervals was quite small, at 175 Hz. In contrast, the difference in average centroid frequency at those same two intervals in the palate conditions was 598 Hz. In addition, for all speakers, the standard errors were slightly higher in the normal condition at T60 relative to T0.

B. Perceptual analyses

The rating values were calculated in millimeters (mm) for each stimulus and means for each palate/time-interval condition were computed. The average ratings (with standard errors) for the four conditions are displayed in Fig. 3. As may be seen, at both time 0 and time 60, the ratings for the palate conditions were lower than those for the normal productions, but the values approximated one another more closely at the later test interval. A test interval×palate condition ANOVA conducted on the ratings (with listener as a random factor) revealed a main effect for palate condition [$F(1,9)=98.118$, $p<0.001$] and a test interval×palate condition interaction [$F(1,9)=33.552$, $p<0.001$].[2]

Post hoc analysis of the interaction using the Newman–Keuls procedure ($p<0.01$) demonstrated that all conditions were significantly different from one another. Of particular interest is the direction of change from time 0 to time 60 for the palate as compared to the normal conditions. In the palate conditions, quality ratings improved substantially from the initial test interval to the final interval; in stark contrast, quality ratings for the normal stimuli decreased over that same

TABLE II. Mean (+s.e.) of [s] centroid frequencies for each subject.

Subject	Without palate	With palate: Measurement periods					Without palate
	0	0	15	30	45	60	60
1	8233 (51)	7356 (70)	7646 (76)	7824 (81)	7992 (84)	8116 (59)	8381 (55)
2	7961 (40)	7299 (63)	7838 (65)	7972 (56)	7847 (65)	7721 (68)	7792 (68)
3	8232 (69)	6956 (80)	7485 (90)	7518 (134)	7681 (77)	7590 (119)	8124 (71)
4	8071 (58)	6854 (190)	7675 (157)	7515 (182)	7867 (72)	7509 (149)	8039 (58)
5	7829 (99)	6655 (88)	6958 (109)	6767 (76)	7069 (85)	6861 (75)	7440 (107)
6	8460 (89)	7069 (97)	6981 (130)	6934 (125)	7382 (93)	7722 (83)	8138 (117)
7	7827 (64)	6794 (66)	7377 (78)	7471 (66)	7732 (88)	7574 (63)	7517 (86)
Mean (s.e.)	8091 (30)	6989 (42)	7423 (45)	7429 (50)	7653 (37)	7587 (42)	7916 (38)

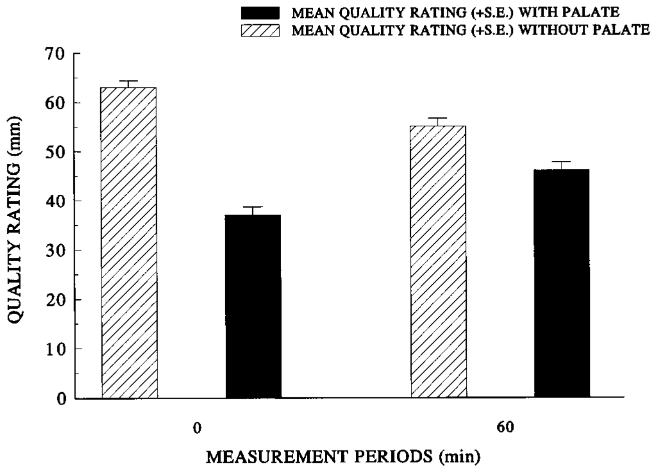

FIG. 3. Mean quality ratings (+s.e.) for the normal and palate conditions at time 0 and time 60.

time period. These data suggest that modifications made to articulatory strategies for [s] to accommodate the artificial palate may have adversely affected the productions without the palate during that 1-h interval.[3]

III. DISCUSSION

The main finding of the present investigation was that adaptation to a structural modification of the oral cavity can occur relatively quickly with intensive, target specific practice. In agreement with our previous observations (McFarland *et al.*, 1996), lower centroid and quality ratings were found for [s] in palate as contrasted to normal (i.e., no palate) conditions, suggesting that this sound is highly susceptible to the perturbing effects of the artificial palate with a thicker than normal alveolar ridge. However, significant improvements in the acoustic and perceptual characteristics of [s] produced with the artificial palate in place were observed after a relatively brief one-hour practice period, although compensation was not complete. Previous reports have suggested that artificial palates placed in the mouths of otherwise normal speakers require a lengthy adaptation period. For example, in a previous study (McFarland *et al.*, 1996), we found no significant improvements in the acoustic characteristics of [s] after a 15-min adaptation interval with an artificial palate in place. Others have suggested that an adaptation period of days or weeks is required before normal speech is approached (Hamlet and Stone, 1976a, b; Hamlet *et al.*, 1978; Hamlet and Stone, 1978). In these earlier studies, however (as noted in the Introduction), there were no controls on the speech activity during the adaptation interval, and subjects may have had varying amounts of target sound production with the artificial palate in place. In the present study, subjects read specifically prepared texts heavily laden with [s], and this led to a relatively rapid improvement in articulatory accuracy.

It seems reasonable to assume that the lower centroid values in the palate as contrasted to normal conditions resulted from subjects moving the point of constriction for [s] production more posteriorly in the oral cavity due to the presence of the artificial palate. That is, subjects may have been ''searching'' for an area of articulation more similar to the one used when normally producing [s] (i.e., with less alveolar thickness), or the presence of the buildup of acrylic in the alveolar area forced a more posterior tongue positioning. Alternatively, the altered centroids under conditions of perturbation may not have resulted from a more posteriorly placed constriction but rather may have been due to modification of the nature of the constriction (due to the increased thickness of the alveolar region) and changes in the direction of the airstream. We can only speculate as to the articulatory movements used in compensating for the presence of the artificial palate and the improvements in production accuracy during the period of adaptation. Perhaps subjects gradually moved the point of constriction more anteriorly and/or modified airflow turbulence in response to auditory and/or oral-sensory feedback.

The gradual improvement in articulation accuracy during the adaptation period suggests that articulatory processes for [s] production were continuously updated and refined (see Gentilucci *et al.*, 1995 for similar findings with reference to the control of precision grasp), perhaps by somatosensory and/or auditory feedback, in response to the change in oral form associated with the artificial palate. In fact, there appears to have been a ''neural recalibration'' (Anstis, 1995) of [s] articulation strategies under conditions of perturbation that persisted after the period of adaptation. While perturbed productions were steadily improving with practice, [s] productions without the artificial palate (normal conditions) were adversely affected, both in terms of quality ratings and acoustic measures, by the one-hour period of practice with the palate in place. ''Normal'' productions appeared to be approaching those of the adapted conditions with the palate in place, indicating that movement control parameters developed for the presence of the artificial palate were inappropriately applied to [s] productions without the palate in place. Similar negative ''aftereffects'' have been observed in other complex systems under conditions of adaptation. For example, in a recent study by Anstis (1995), subjects were asked to jog in place on solid ground after a 60-s period of adaptation to running on a treadmill. Once on solid ground, subjects tended to jog forwards, presumably because of persistent adaptive modifications of the gait control system for treadmill running (Anstis, 1995). Studies of second-language acquisition provide additional evidence for adaptive or common modes of speech articulatory programming (for a review, see Flege, 1988). Results reveal that learning a second language, particularly at a later age, may affect the production (and perception) of the native language, and the phonetic properties of the speech sounds (e.g., VOT) in the two languages may assimilate to common values (Flege, 1988). To extend and further evaluate the present findings, it would be important to observe normal and compensatory articulation during an even longer period of articulatory practice and at selected time intervals after the adaptation period.

The relatively short duration of the adaptation period in the current study sets the stage for the analysis of the potential influence of sensory feedback in the development of speech adaptation. As in a variety of complex motor behaviors (and as noted above), somatosensory and/or auditory feedback may have been utilized in updating the speech motor control system under conditions of perturbation (Gentilucci *et al.*, 1995). Auditory feedback may be particularly crucial for the development of speech motor control (Osberger and McGarr, 1982), and has been implicated in the on-line monitoring of at least some aspects of speech articulation (Perkell *et al.*, 1992; Waldstein, 1990). That there may be some auditory-based correction of speech articulatory gestures is also suggested by the clinical observation that adaptation to dentures is lengthened in patients with hearing loss (Martone, 1962). An obvious next step, and one that has been used rather frequently in speech motor control research (Smith, 1992), would be to modify or eliminate auditory feedback and to observe the effects, if any, on the duration or form of the adaptation process.

Somatosensory feedback which may participate in the adaptation process is also available from a variety of intraoral cutaneous afferents (Kent *et al.*, 1990; McFarland and Lund, 1995; Smith, 1992). Information from these sources might be used in assessing the status of the oral-motor system at the time of movement initiation and in modifying central command signals for speech articulation in the face of perturbation (Smith, 1992). Signals from intraoral afferents may be particularly important for certain sound classes, such as sibilants, which require a precise positioning of the tongue relative to the palatal surface. In fact, the presence of the artificial palate might be expected to modify or eliminate signals coming from palatal mucosal afferents. Subsequent work could focus on the further modification of these and other oral feedback channels, perhaps in combination with interruptions to auditory feedback (Kelso and Tuller, 1983).

The fact that intensive practice seems to modulate the time to adapt to a structural modification of the oral cavity [as indicated in comparison of the present study with our earlier findings (McFarland *et al.*, 1996) as well as those of others (e.g., Hamlet, 1973; Hamlet and Stone, 1974, 1978; Hamlet *et al.*, 1979)] may also have important clinical implications. Clinical observations suggest that the presence of dental prostheses and orthodontic appliances (Chaney *et al.*, 1978; Palmer, 1979; Tanaka, 1973) can result in significant speech articulation errors. Sibilants appear to be particularly impaired, and in fact, [s] production is often used to modify dental prostheses to improve their speech function (Pound, 1970, 1977). Although clinical reports suggest that most patients eventually compensate for the articulatory disturbances associated with dental appliances, there appear to be considerable differences between patients in their ability to adapt, and sibilants appear to be particularly resistant to adaptation (Tanaka, 1973). Perhaps intensive practice on target sound production would facilitate speech sound production in these clinical cases. Specific feedback on key articulatory configurations and/or movements may also facilitate the adaptation process. It would be important, in this regard, to record not only speech acoustics but also articulatory movements under conditions of perturbation, and although technically demanding, it seems particularly relevant to record movements of the tongue relative to the palatal surface. Previous investigations have shown that some speakers are able to alter tongue groove shapes, apparently critical to accurate [s] production, in response to specific articulatory feedback (Fletcher and Newman, 1991).

IV. CONCLUSION

In conclusion, the results of the present investigation have revealed that speech compensation to the presence of an artificial palate can occur quickly during a relatively brief, target-specific period of practice. Future investigations may be directed toward exploring the potential contribution of sensory feedback in the adaptation process as well as the clinical utility of manipulating adaptation to dental prostheses and other clinically relevant modifications of the oral cavity. Further work is also needed in exploring the potential distributed effects of adapted articulatory strategies to non-perturbed speech articulation. Our preliminary data suggest that speech adaptation to oral-articulatory perturbations may result from a recalibration of the speech motor control system and a common or adaptive mode of articulatory programming distributed across perturbed (adapted) and normal [s] productions. Obvious parallels to similar effects in other complex systems provide added importance for further study of this preliminary finding.

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[1]Although these individuals had had some experience with [s] production with the palate in place, only 30 tokens had been produced in the previous experiment, which had been conducted more than 1 year earlier. As will be seen, there were no differences in production between the subject without prior experience and the others, suggesting that the previous limited experience with [s] production with the palate in place had little or no effect on performance in the current study.

[2]An ANOVA was also conducted using speaker as a random factor, and this analysis revealed the same pattern of results: a main effect for palate condition [$F(1,6)=6.86$, $p<0.05$] and a test interval×palate condition interaction [$F(1,6)=8.62$, $p<0.05$].

[3]In a comparison of acoustic and perceptual data, although overall trends patterned similarly, there were some discrepancies for individual subjects. That is, for certain speakers, the perceptual ratings did not correspond well with the acoustic findings. This is most likely due to listeners' reliance on acoustic parameters other than those measured in the present investigation in making their perceptual judgments.

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