

Velopharyngeal Function: A Spatial-Temporal Model

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I. INTRODUCTION

Speech sounds are produced by modulating the glottal air stream within the vocal tract (Fant, 1971; Stevens & House, 1955, 1961). For oral phonemes, the vocal tract may simply be viewed as a tube consisting of the pharyngeal and oral cavities, augmented for the production of nasal phonemes by an additional branched tube coupled to the pharyngeal and oral cavities. The ability to control coupling of the nasal cavities to the pharyngeal and oral cavities is crucial for the production of normal speech. Inability to decouple the nasal cavities from the remainder of the

vocal tract will result in severely distorted speech. In addition, speakers must be able to control, with some precision, the timing of alternating these coupled and decoupled configurations of the vocal tract in order to realize phonemic distinctions between nasal and oral segments.

This article offers a description of the control system that governs the coupling and decoupling of these resonating cavities, beginning with a brief summary of the mechanisms for closing and opening the velopharyngeal port in speech, and then considering, in some detail, the effects of phonetic content on velar position. Following this phonetic-content description is a phonetic-context description of velar function concerned with considering the interaction between velar movement patterns for proximate phonetic segments.

Phonetic context effects are interesting because of the insights that they may provide into the form of the motor plan for speech: In what units is the motor program specified, and over what number of these units is it prepared? One way to gauge the degree to which we understand a system (for example, the form of the motor plan employed for speech) is to build a model embodying the known facts and then to examine the model's ability to predict the behavior of the natural system under novel conditions. The success of the model in predicting the behavior of the system is, then, an index of the caliber of our understanding. This is a time-honored test of great usefulness and therefore, employing the velar coarticulation data reported in the literature, as well as data from an experiment to be reported here, we propose to offer a model of velar function that may prove to be a useful subject for further comparisons with the actions of the human articulatory system.

II. MECHANISMS OF VELAR CONTROL

A. Introduction

The role of the velopharyngeal mechanism in speech has been of interest for many years, but the history of this interest will be surveyed only briefly in this article. (See Dickson & Maue-Dickson, 1980, for a comprehensive historical perspective.) Thus, Fritzell (1969) reports studies by Czermak (1857, 1858, 1869) and Passavant (1863) involving both indirect and direct measures of velopharyngeal closure during speech.¹

¹ It is possible to observe articulator movements associated with speech gestures in two fundamentally different ways (cf. Bell-Berti, 1973). The first of these, direct viewing, involves measurement of articulator position, for example, measuring the elevation of the velum over time. Such techniques include visual observation (using

The conclusion of these experiments was that velar height decreases through the vowel series [i], [u], [o], [e], [a]. Passavant also placed tubes of varying diameters in the velopharyngeal port region to determine how small the port must be to prevent nasalization of oral speech sounds. He found that a cross-sectional area of 12.6 mm² had little effect on speech quality, but that a cross-sectional area of 28.3 mm² resulted in the nasalization of most consonants. He also reported a bulging in the posterior pharyngeal wall, above the level of velopharyngeal closure, during the speech of a cleft palate speaker, and assumed that this bulging, which has come to be known as **Passavant's ridge**, occurs in all speakers.

It is possible to trace two lines of investigation leading from these early studies. The first line concerns the dimensions and mechanisms of oral and nasal articulation. More specifically, is oral articulation achieved by: (a) posteriorly and superiorly directed movement of the velum; (b) a combination of velar movement and anteriorly directed movement of the posterior pharyngeal wall (Passavant's ridge); or (c) a combination of velar movement and medially directed movement of the lateral pharyngeal wall? Which muscles are responsible for closing the velar port? Need the port be completely closed for all 'oral' articulations? Is nasal articulation achieved by the contraction of some muscle or muscle group, or solely by decreasing activity in those muscles responsible for oral articulation? The second line of investigation concerns the nature of variations in velopharyngeal activity both as a function of the identity of phonetic segments and as a function of interactions among proximate segments (coarticulation).

B. Velopharyngeal Closure Mechanisms

It is generally accepted that the levator palatini is the muscle responsible for elevating and retracting the velum (cf. Bell-Berti, 1976; Bosma, 1953; Dickson, 1975; Fritzell, 1969; Lubker, 1968). This upward and backward motion of the velum is observed in all normal speakers.

The questions concerning velopharyngeal closure mechanisms that continue to receive attention and will briefly be considered here involve the roles of the posterior and lateral pharyngeal walls in the closing gesture. The first of these, the question of the existence and ubiquity of Passavant's ridge as a mechanism for closing the velar port, has been

posterior rhinoscopy or endoscopy) and cinematography, cineradiography, ultrasonic echo recording, and photoelectric recording of reflected light. The second group of methods, **indirect viewing**, involves measurements of the cause or result of articulator position or displacement, implying but not specifying articulator movements, including electromyographic, air flow, acoustic, and transillumination recordings.

addressed by a number of investigators. For example, Calnan (1957) has disputed the presence of Passavant's ridge in most speakers and claimed that such a mechanism would be far too sluggish and fatigable to be a reliable compensatory mechanism for speakers with inadequate palatal musculature. Hagerty and colleagues (Hagerty & Hill, 1960; Hagerty, Hill, Pettit, & Kane, 1958) concluded that Passavant's ridge is not a mechanism used by most normal speakers, although postoperative cleft palate subjects tend to use more posterior pharyngeal wall movement in speaking than do normal subjects. Carpenter and Morris (1968) concluded that, when Passavant's ridge occurs in speakers with surgically repaired clefts, it may be used as a reliable compensatory mechanism for some of them. In parallel studies of normal and cleft palate speakers, Björk (1961) and Nylen (1961), respectively, found that normal speakers did not use anteriorly directed movement of the posterior pharyngeal wall in closing the velar port, and that among cleft palate speakers judged to have no insufficiency, velar movement patterns were comparable to those of normal speakers. In addition, a Passavant's ridge was identified in 11 of Nylen's 27 speakers whose velopharyngeal closure was judged to be inadequate for speech.

Observations of anteriorly directed movements of the posterior pharyngeal wall have been attributed to contraction of the superior pharyngeal constrictor. Similarly, the regularly observed medial movements of the lateral pharyngeal walls, at the level of velopharyngeal closure, have also been attributed to the action of this muscle (cf. Fritzell, 1969; Lubker, 1968; Shprintzen, Lencione, McCall, & Skolnick, 1974; Skolnick, McCall, & Barnes, 1973; Zagzebski, 1975). However, this view is difficult to support anatomically because the superior margin of the superior pharyngeal constrictor is at or below the palatal plane (Dickson, 1975), and velopharyngeal closure is frequently above this level. It therefore seems unlikely that the superior pharyngeal constrictor can be responsible for these movements. Furthermore, the converging movements of the lateral walls and velum are strikingly parallel in both time course and extent (cf. Harrington, 1944; Niimi, Bell-Berti, Harris, 1978; Skolnick, 1969; Zagzebski, 1975). Finally, the weight of evidence from electromyographic studies on the role of the superior pharyngeal constrictor in closing the velar port is divided, with supportive data reported by Fritzell (1969) and Lubker (1968) and conflicting data reported by Bell-Berti (1973, 1976) and Minifie, Abbs, Tarlow, and Kwaterski (1974).

An alternative view is that both lateral pharyngeal wall movement and velar elevation and retraction are caused by contraction of the levator palatini (cf. Bell-Berti, 1973, 1976; Bosma, 1953; Dickson, 1975; Dickson & Dickson, 1972; Honjo, Harada, & Kumazawa, 1976; Niimi *et al.*, 1978).

However, some investigators have claimed that because the localized bulge in the lateral walls occurs below the level of the "levator eminence" (on the superior surface of the velum), the bulge cannot result from contraction of the levator palatini (cf. Shprintzen *et al.*, 1974; Skolnick *et al.*, 1973). But the studies of Azzam and Kuehn (1977) and of Dickson (1972) indicate that the "levator eminence" may result from contraction of the uvular muscle, and not of the levator palatini, thus casting doubt on the validity of the argument.

It is not clear, then, whether or not the superior pharyngeal constrictor plays a role in closing the velar port for speech. It does, however, seem reasonable to attribute to it, and to the middle pharyngeal constrictor as well, some portion of the lateral pharyngeal wall movement observed in the oropharynx for open vowels (cf. Minifie, Hixon, Kelsey, & Woodhouse, 1970; Zagzebski, 1975). This seems especially reasonable in light of EMG data showing parallel activity in the pharyngeal constrictor muscles, at the level of the epiglottis and at the superior boundary of the superior pharyngeal constrictor, for speech (Bell-Berti, 1973, 1976).

C. Velopharyngeal Closure: Critical Port Size

A second question raised by studies of velar port control is whether the port must be completely closed for all oral phonemes to prevent coupling of the nasal and oral cavities. In experiments with synthesized speech, House and Stevens (1956) varied the ratio of the driving point impedance of the velopharyngeal port (which is a function of the port's cross-sectional area) to the internal impedance of the vocal tract, and found that nasal coupling increased as this ratio decreased. They reported that listeners failed to judge any of their vowel stimuli produced with a port area of 25 mm² as "more nasal" than those produced with the port completely closed, but that high vowels produced with a port area of 71 mm² (the next larger area in their series) were judged as "more nasal" than those produced with the smaller area.

Björk's (1961) report provides us with a useful rule of thumb for estimating port area from lateral view X-ray pictures. He found the cross-sectional area of the port to be a linear function of the port's sagittal minor axis, and that the area may be computed by multiplying the anteroposterior dimension of the port (expressed in millimeters) by 10. Applying Björk's computation to anteroposterior dimension data available in the literature, we find, in general, that speakers having minimum velar port areas of less than about 30 mm² had speech that was nearly normal, while those having greater minimum port areas had speech judged as

being nasalized. Indeed, the larger the minimum port area, the more seriously distorted with the speech (cf. Nylen, 1961; Subtelny, Koeppe-Baker, & Subtelny, 1961). In agreement with these data are those of Warren's (1967) study of nasal air flow as an estimate of velar port size: speech was judged adequate at minimum port areas under 20 mm^2 and inadequate when the minimum port area was greater than 20 mm^2 . The results of Isshiki, Honjow, and Morimoto (1968), who induced velopharyngeal incompetence in their subjects by placing polyvinyl tubes in their velar ports and found the critical port area to be about 20 mm^2 , further substantiate the results of speech synthesis and physiological studies.²

Thus, complete closure of the port is not always required for normal speech production. The speaker need only make the port sufficiently small so as to establish admittances into the nasal, oral, and pharyngeal branches, at the velar port, that will prevent the nasal branch from affecting the overall vocal tract transfer function for sonorants. For obstruents, the port must also be sufficiently small to prevent nasal air flow. Indeed, Björk (1961) reports the presence of a gap between the velum and posterior pharyngeal wall during the production of some obstruent segments judged as completely normal (see Section VI for a discussion of the acoustical theory of nasality).

D. Velopharyngeal Port Opening Mechanisms

A third question is how the velar port is opened to permit nasal coupling. There are two ways in which the velar port could be opened. The first, and simplest, is that the muscles used in closing it relax and the elastic tissue forces open the port. The second possibility is that the contraction of some muscle or group of muscles (possibly palatopharyngeus or palatoglossus) pulls downward on the velum while the muscles involved in closing the port are relaxing.

In an EMG study, Fritzell (1969) found palatopharyngeus activity to vary across subjects but in general to be more active for the vowel [a] than for [i] and [u]. Bell-Berti (1973, 1976) has reported that the palatopharyngeus works synergistically with the levator palatini, but that it is more active for open than for close vowels, apparently acting to narrow the faucial isthmus for these articulations. Thus, the available EMG data do

² It is of some interest to note that all of these fairly recent data provide general confirmation of Passavant's (1863) report that a velopharyngeal port cross-sectional area of 12.6 mm^2 had little effect on the quality of speech, while a cross-sectional area of 28 mm^2 resulted in nasal coupling for oral speech sounds and, thus, in distorted speech.

not provide support for the role of the palatopharyngeus as a velar depressor.

The situation is less clear, however, for the palatoglossus. Several studies have reported that palatoglossus activity occurs when levator palatini activity is suppressed; that is, at times corresponding to nasal consonant articulation (cf. Benguerel, Hirose, Sawashima, & Ushijima, 1977; Fritzell, 1969; Lubker, Fritzell, & Lindquist, 1970; Lubker, Lindquist, & Fritzell, 1972; Lubker & May, 1973). In contrast, however, Bell-Berti (1973, 1976; Bell-Berti & Hirose, 1973) reported EMG data, recorded from several speakers, showing no difference in palatoglossus activity associated with changes in the status of the velar port. Instead, these data show palatoglossus activity for high back vowels and velar consonants, speech segments for which levator palatini activity is also high (see also Kuenzel, 1978), indicating palatoglossus involvement in tongue-dorsum elevation. In addition, these authors have reported recording palatoglossus activity for low vowels, presumably to narrow the faucial isthmus. Finally, Bell-Berti and Hirose (1973) obtained data for one speaker who apparently uses the palatoglossus in both tongue-dorsum elevation and velum-lowering gestures.

Taken together, these data suggest, at the least, that there is no universal mechanism for lowering the velum involving increased activity in any muscle (Bell-Berti, 1976). Rather, the basic mechanism for opening the velar port involves the suppression of activity in those muscles acting to close it, and for some speakers the contraction of the palatoglossus is used to provide a supplementary downward force. However, there is no evidence that the palatopharyngeus ever provides such a force.

III. THE EFFECTS OF PHONETIC CONTENT

Closely related to the question of how the velopharyngeal port is closed to achieve oral articulation is the question of how tightly closed it must be, for a given segment type, to prevent nasal coupling. This question is obviously related to the effect of phonetic content upon velar height. However, these two aspects of the question will be considered separately to ensure a thorough appreciation of the segmental effects.

A number of investigators (e.g., Moll, 1962) have concluded that velar port closure and, hence, velar elevation are greater for high vowels than for low vowels and that closure is incomplete for vowels in nasal environments. One explanation given for these differences in articulator position includes the mechanical constraints within the articulatory system and changes in the timing relationships among the control signals to the

articulators (cf. Lindblom, 1963; Stevens & House, 1963). Thus, one possible description of velar position control might be an "on-off" algorithm with variable control-signal timing relationships and a correction for mechanical constraints.

However, this view has been disputed by the evidence from a number of studies (cf. Bell-Berti, 1976; Fritzell, 1969; Lubker, 1968; Moll & Shriner, 1967). For example, Fritzell (1969) and Lubker (1968) reported a high correlation between velar position and velar EMG activity for vowels of different height, with greater elevation and EMG potentials for high vowels than for low vowels. These data, and others not enumerated here, confirm the reports of Czermak (1857, 1858, 1869) and of Passavant (1863) that palatal height increases through the series [a], [e], [o], [u], [i].

Extending our view to consonantal segments, we find, not surprisingly, that nasal consonants have the lowest velar position and smallest levator palatini EMG potentials of any speech sounds (cf. Bell-Berti, 1976; Bell-Berti, Baer, Harris, & Niimi, 1979; Fritzell, 1969; Lubker, 1968). Conversely, obstruent consonants have the highest velar elevation and largest levator palatini EMG potentials (cf. Bell-Berti, 1976; Bell-Berti & Hirose, 1975; Harris, Schvey, & Lysaught, 1962; Lubker *et al.*, 1970).

It is clear from the data of many studies, carried out over more than a century on several different languages, that it is possible to make at least one general statement about the relationship between velar elevation and the phonetic content of a piece of speech. Velar elevation and levator palatini EMG potentials for oral speech sounds vary directly with the degree of oral cavity constriction, decreasing through the series: obstruents—close vowels—open vowels. In addition, the results of perceptual tests of the effects of opening the velar port reveal that oral consonants are distorted at smaller port areas than are close vowels which, in their turn, are perceived as being "nasal" at smaller port areas than are open vowels. Since velar elevation decreases through this same series, we might conclude that speakers recognize the acoustic consequences of inappropriately large velar port areas and modify velar port area (by controlling velar elevation) to avoid introducing the distortions of nasal coupling.

However, some disagreement remains about levator palatini EMG potential relationships and velar position relationships within the group of obstruent consonants. It has been suggested that those consonants characterized by high intraoral air pressure levels (e.g., the high-intensity voiceless fricatives) are produced with the strongest levator palatini EMG potentials (cf. Lubker *et al.*, 1970). There are, however, reports of velar function differences among speakers, differences indicating that the voiceless obstruents are produced with the strongest levator palatini

activity only by some speakers (Bell-Berti, 1973, 1975; Bell-Berti & Hirose, 1975). These differences among speakers are systematic and are related to the different articulatory strategies used by the speakers to maintain voicing during obstruent consonant production (cf. Bell-Berti, 1975). Thus, some speakers regularly use greater levator palatini activity (and, consequently, higher velar elevation) for voiced obstruents than for their voiceless cognates, increasing the volume of, and decreasing the supraglottal pressure in, the pharyngeal cavity. This adjustment maintains the translottal pressure difference required for glottal pulsing to continue during the period of vocal tract occlusion for obstruent production (cf. Bell-Berti, 1975; Perkell, 1969; van den Berg, 1958). Conversely, some speakers maintain the transglottal pressure difference necessary for glottal pulsing by allowing air to "leak" through a partially opened port (Dixit & MacNeilage, 1972). Still other speakers accomplish this vocal tract adjustment in other ways, including advancing and depressing the tongue root, depressing the larynx, or increasing oral cavity volume (cf. Bell-Berti, 1975; Fujimura, Tatsumi, & Kagaya, 1973; Kent & Moll, 1969).

These secondary articulatory maneuvers controlling effective pharynx volume, as well as the adjustment of pharyngeal cavity cross-sectional area for vowels (see Bell-Berti, 1973), are important for two reasons. First, and most obvious, is that an adequate model of speech production must account for all of the articulatory activities of the speech mechanism. Second, and perhaps of more direct relevance here, their interaction with port-closing gestures might otherwise confuse our interpretation of data collected during the production of long sequences of segments, which we must collect if we are to improve our understanding of the interaction between motor plans for, and/or the execution of, speech.

IV. THE EFFECTS OF PHONETIC CONTEXT

In addition to describing the mechanisms of oral and nasal articulation and their interaction with phonetic content, studies of velar function have also tried to define, usually in terms of segmental units, the extent of the influence of velar position for one segment on velar position for proximate segments in order to gain insight into the size of the units of the speech motor plan. Most often, the focus has been on the influence of velar position for nasal consonants on velar position for vowels. Indeed, it is a common observation that vowels adjacent to nasal consonants are nasalized (see Leutenegger, 1963) and, more specifically, that nasality is assimilated in vowels before nasal consonants (Bronstein, 1961). Ohala (1971) has reported greater nasal coarticulation effects in vowels preced-

ing than in vowels following nasals and states that velar lowering begins as soon as elevation is no longer required for obstruent articulation. Ushijima and Sawashima (1972) found that vowels in nasal environments have lower velar positions than do the same vowels in oral environments, and that the greatest velar elevation occurs for obstruent consonants immediately following nasals. In a study having a somewhat different objective, one describing the effects of vowel environment on velar position for consonants, the velum was found to be higher for both oral and nasal consonants occurring in close-vowel than in open-vowel environments (Bell-Berti *et al.*, 1979).

In an account of a study of the timing of velar movements in relation to other, segmentally defined, articulator movements, Moll and Daniloff (1971) reported that movement toward opening of the velar port began during articulator movement toward the first vowel in CVN and CVVN sequences. In NC and NCN sequences, movement toward closure began during the first nasal consonant. In NVC sequences, movement toward closure was quite similar to that for NC sequences, although it began a bit later in the former and closure was not always complete during the vowel.

One general model of speech production that has been tested with velar function data is Henke's (1966) phoneme-based model. This model assumes the input to the articulatory system to be a string of phonemes that are specified as sets of invariant articulatory goals, or "features." It postulates a "look-ahead" procedure that allows the goals of phonemes occurring later in the string to influence the current and intervening vocal tract configurations, so long as these anticipated goals are not in conflict with any more immediate goals.³ A model developed from the Moll and Daniloff data proposes two velar port goals: "closed" for oral consonants and "open" for nasal consonants. In this scheme, velar position for vowels is assumed to be unspecified and determined by the next specified position. The predictions of this essentially binary model agree with those of Henke's model of speech production, and a substantial proportion of the data is in agreement with the predictions of such a look-ahead model.

There are, however, at least three instances in which blind application

³ Another frequently examined model of speech production, that of Kozhevnikov and Chistovich (1965/1966), posits larger units, "articulatory syllables," as the basic units of the speech motor program. The articulatory syllable is described as a CV string, with C being any number of consonants. While this model accounts for some coarticulation data, it completely fails to account for velar function data: the common observation is that the nasality of a consonant is anticipated in a preceding, not following, vowel. Therefore, unless we assume that the organizational units of the motor program are different for different articulators, this model can be eliminated from further consideration.

of the look-ahead model fails to account for observations of human speech. The first of these is the reported effect of a marked junctural boundary in blocking anticipation of a downstream goal (McClellan, 1973; Ushijima & Hirose, 1974). McClellan suggests that the delay in nasal anticipation may result from a high-level reorganization of commands to the velum and that this explanation is consistent with a look-ahead model. The second discrepancy between the data and the look-ahead model concerns predictions of timing. For example, in NC sequences, velar movement toward closure often begins before the oral constriction for the nasal consonant is achieved. Kent, Carney, and Severeid (1974) suggest that the binary model need only be modified to allow a motor program that simultaneously issues commands to different articulators for different segments. The third, and to this view the most serious, failure of the binary model concerns the prediction of velar height for vowels in utterances whose consonants are either all oral or all nasal. In such phoneme sequences velar height is not constant, as the model predicts, but rather decreases for vowels occurring within oral consonant environments (Bell-Berti, 1979) and increases for vowels occurring within nasal consonant environments (Kent *et al.*, 1974), in direct contradiction with the prediction that the velar goal for the consonants will be anticipated during the vowels.

Finally, there are two additional problems surrounding the development of an adequate model of velar function that stem from limitations in the quality of many of the existing data. These limitations in turn result from shortcomings in the design of many of the experiments. For example, the restricted nature of the phonetic inventory in the speech samples that have been studied renders impossible many of the comparisons between oral- and nasal-environment effects that might reveal the segmental, or temporal, extent of the coarticulatory field. That is, since it has been assumed that nasality is the only phonetic feature whose presence will influence velar height for nonnasal segments, nearly all of the speech samples contain nasal segments. Those sequences not containing nasal segments are contrasted with utterances which do contain nasals, and not with other, minimally contrastive, nonnasal utterances.

A second, and more serious, limitation is imposed by the tacit assumption that velar position for vowels between oral consonants will be the same as velar position for the oral consonants, in face of the substantial body of contrary data indicating that velar position for oral speech sounds varies directly with the oral cavity constriction for those sounds (cf. Bell-Berti, 1973, 1976; Czermak, 1857, 1858, 1869; Fritzell, 1969; Lubker, 1968; Moll, 1962; Passavant, 1863). That this assumption has often been made is evident in the criteria for establishing the beginning of anticipa-

tory influences of nasal consonants on preceding vowels, usually taken as the earliest observation of velar lowering after peak elevation for the oral consonants in CVN sequences. It is obvious, however, from the data of Fig. 1 that the velum lowers for vowels following obstruent consonants even when those vowels occur in entirely oral environments. Thus, it is impossible to estimate the extent of the anticipatory field from measures of the earliest moment of velar lowering in CVN sequences since this lowering may be associated with the velar-position specification for the vowel. Rather, descriptions of the timing of anticipatory nasal coarticulation must derive from comparisons of velar position for vowels in both oral and nasal environments.

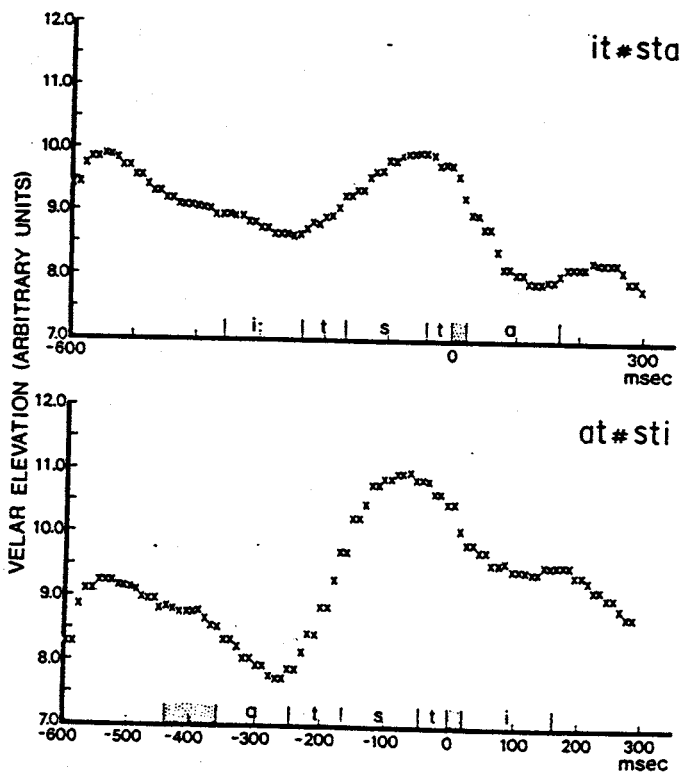


Figure 1. Ensemble-average velar elevation functions for two $V_1C_nV_2$ phrases from the utterance set described in Section V,B,1, spoken in the carrier sentence *It's a _____ again*. The upper figure contains the function for the phrase [flit#stap]; the lower figure contains the function for the phrase [kat#stiz]. Velar elevation is given in arbitrary units; time in milliseconds. Average durations of the segments of $V_1t\#stV_2$ are displayed beneath each function. Zero on the abscissa represents the acoustic end of the consonant string.

V. A SPATIAL—TEMPORAL MODEL OF VELAR FUNCTION

A. Preliminaries

The model offered here is intended to account for observations of velar position and the timing of velar movements in normal speech. This model assumes that the levator palatini is the muscle primarily responsible for velopharyngeal closure and that the strength of levator palatini contraction is reflected relatively directly in velar position. This assumption is based on the knowledge that the area of the velopharyngeal port is closely related to the position of the velum, with port area decreasing directly with increasing velar elevation (Ushijima & Sawashima, 1972). In addition, we know the levator palatini muscle to be responsible for raising and retracting the velum in the port-closing gesture (cf. Bell-Berti, 1976; Fritzell, 1969; Lubker, 1968). However, since upward movement of the velum may continue above the level at which the port closes completely, measures of velar elevation more directly reflect the motor commands underlying velar gestures than do measures of velar port area.

The data on which this model rests include electromyographic and positional information recorded from the velum, much of which has been reported elsewhere (cf. Bell-Berti, 1973, 1976, 1979; Bell-Berti *et al.*, 1979; Bell-Berti & Hirose, 1975). Briefly, EMG recordings from the levator palatini have shown the magnitude of its EMG potentials to correlate highly with changes in velar position (Bell-Berti & Hirose, 1975) within a constant phonetic environment. These potentials are greatest for obstruent consonants, smaller for close vowels, smaller still for open vowels, and lowest for nasal consonants (cf. Bell-Berti, 1973, 1976). In addition, velar height decreases through the same series, highest for obstruents and lowest for nasals (cf. Bell-Berti *et al.*, 1979; Bell-Berti & Hirose, 1975).

In addition, velar position data were collected in an experiment to supplement existing data, providing information on coarticulation within entirely oral utterances. These data permit one to examine the temporal extent of interaction effects among vowels and consonants in entirely oral utterances and are described below.

B. The Experiment

1. Methods

The subject in this study was a native speaker of standard greater metropolitan New York City English. The experimental utterances were

27 two-word phrases having the general form $V_1C_nV_2$. V_1 and V_2 were [i] and [a], respectively, in 15 of the phrases and the converse in the remaining 12 phrases. C_n consisted of combinations of [s] and [t], with word-boundary positions systematically varied in each of the vowel-order sets. This produced such contrasts as, for example, [it#sta], [at#sti], and [ats#ti]. Nine minimal contrasts were possible between vowel-order sets, in addition to the possible contrasts within each vowel-order set among utterances having consonant strings of different duration (and number of segments). Each phrase began and ended with an obstruent consonant, although different consonants began and ended the two sets. The 27 phrases were embedded in the carrier sentence, *It's a _____ again*, and placed in lists in random order. The lists were repeated until the subject had produced from five to eight tokens of each.

A flexible fiberoptic endoscope (Olympus VF Type O) was inserted into the subject's nostril and positioned so that it rested on the floor of the nasal cavity with its objective lens at the posterior border of the hard palate, providing a view of the velum and lateral nasopharyngeal walls from the level of the hard palate to the maximum elevation of the velum. A long, thin plastic strip with grid markings was also inserted into the subject's nostril and placed along the floor of the nasal cavity and over the nasal surface of the velum to enhance the contrast between the edge of the supralvelar surface and the posterior pharyngeal wall.

Motion pictures of the velum were taken through the endoscope at 60 frames per second. The position of the high point of the velum was then tracked, frame-by-frame, with the aid of a small laboratory computer. The measurements of velar elevation for the tokens of each utterance type were aligned with reference to the acoustic boundary between the end of the consonant string and the beginning of the second vowel, and frame-by-frame ensemble averages were calculated. Vowels and medial consonant durations were measured from the digitized audio waveforms of the speech samples of each repetition.

2. The Data

There are two general qualitative observations that can be made about these data. The first, and most striking, is that the velum continues to rise throughout consonant strings of considerable length—as many as five segments and as long as 360 msec—occurring in oral environments. This characteristic of velar behavior illustrates both the nature of the speech motor program and the size of the motor program units and suggests that articulatory gestures may be programmed as movements and not as fixed articulatory targets or goals. Alternatively, the individually specified positional goals for segments may sum cumulatively and even the most

extreme goal may be exceeded. Yet another alternative, again one assuming positional goals, is that the velar goal may not be achieved even during the production of a string of five obstruent segments having a duration of 360 msec. Implicit in this last hypothesis is a velar position goal that far exceeds the velar position necessary to prevent nasal coupling.

The second observation, already mentioned briefly above and which admittedly cannot be separated from the first, is that velar position for vowels differs from velar position for oral consonants. The obvious conclusion, therefore, is that the velar goals for vowels differ from those for consonants. Furthermore, the goals for open and close vowels, at the least, may very well differ from each other.

Several more specific, quantitative observations are also possible. One observation concerns differences in velar position for different vowels. Another concerns the relationships between vowel environment and maximum velar elevation for a consonant string. Still other observations are concerned with the time course of velar elevation and lowering in relation to other articulatory, and acoustic, events.

Turning attention first to velar position for the vowels [i] and [a], elevation was greater for [i] than for [a] in each of the 18 possible (nine first- and nine second-syllable) comparisons [$t(17) = 2.30, p > .05$]. These differences, seen in Fig. 2, were more pronounced in the second than in the first syllable [$V_2: t(8) = 4.95, p < .01$; $V_1: t(8) = 1.88, p < .05$], possibly reflecting differences between syllables in lexical stress and/or the phrase-initial or phrase-final consonant.

Vowel environment had a significant influence on velar elevation for consonants: peak elevation was greater for [aC_ni] than for [iC_na] phrases in all minimal comparisons and, on the average, in 12 [aC_ni] and 15 [iC_na] phrases. The average difference in peak elevation, between vowel-order sets, was highly significant [$t(25) = 6.24, p < .001$] and indicates that the influence of V_2 on peak elevation for consonants is greater than that of V_1 (Fig. 3). Since the peak in the velar elevation function is nearer to V_2 than V_1 , this difference in vowel influence may simply reflect the temporal proximity of the beginning of V_2 to the velar elevation peak. On the average, peak elevation occurs 75 msec before the (acoustic) beginning of the second vowel and the average duration of the medial consonant strings is 226 msec.

In addition to being conditioned by the following vowel, peak velar elevation is also strongly influenced by the duration of the medial consonant string within each vowel-order set (Fig. 4). Thus, there is a strong positive correlation between the duration of the consonant string and maximum elevation, with $r = .74$ for the [aC_ni] phrases and $r = .86$ for the [iC_na] phrases. The lower correlation for the former probably reflects

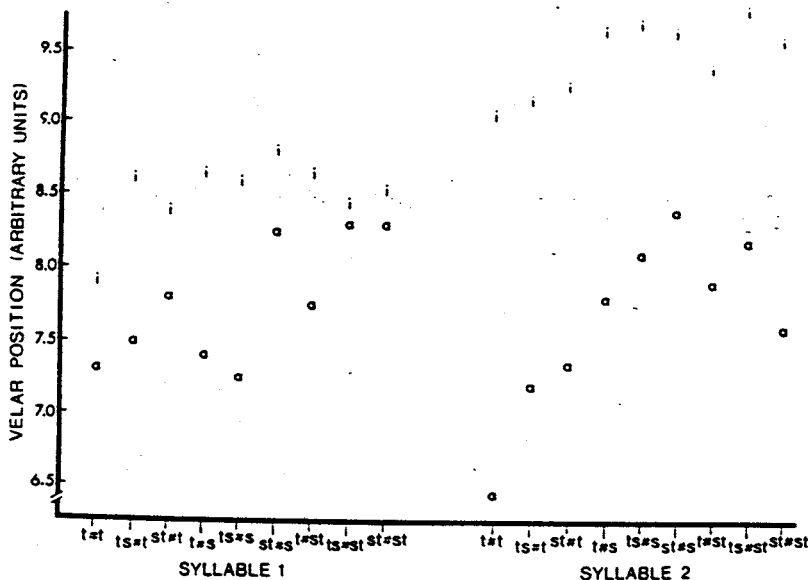


Figure 2. Velar position minima for the vocalic portions of the first and second syllables of the phrases described in Section V.B.1. Velar elevation is given along the ordinate in arbitrary units. Minimal-contrast phrases are represented along the abscissa by their consonant strings; syllable 1 is at the left, syllable 2 is at the right.

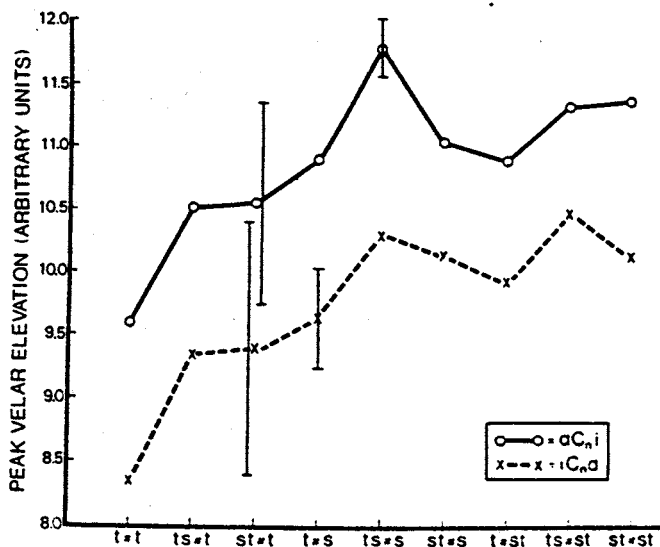


Figure 3. Peak velar elevation, from the ensemble averages, for minimal contrasts indicated along the abscissa. The smallest and largest standard deviation values are shown bracketing their respective means.

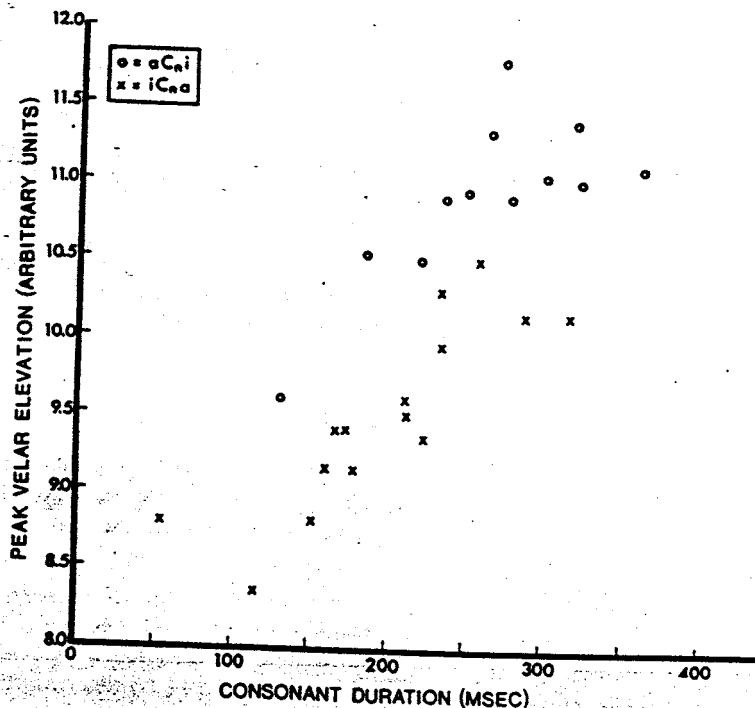


Figure 4. Scatter-plot of peak velar elevation (along the ordinate) vs consonant-string duration (along the abscissa).

the smaller range of peak velar elevations within that group. This reduced range may, in turn, be the result of mechanical constraints that impose ceiling effects on velar elevation possibilities. That is, velar elevation was already so extreme that even large increases in levator palatini contraction could not produce substantial increases in elevation.

Finally, to estimate the time at which V_2 exerts more influence on peak elevation than does V_1 velar elevation was compared in the nine minimal pairs at several times before peak elevation was achieved: at 100, 150, 200, and 250 msec before the beginning of V_2 . The mean difference in velar position was determined for each time point by subtracting the value obtained for [iC_na] strings from that obtained for [aC_ni] strings. As long as V_2 exerts the greater influence, this difference should be positive and it should decrease as the influence of V_2 diminishes, becoming negative when the influence of V_1 exceeds that of V_2 . These data are summarized in Table I. Clearly, at even 100 msec before V_2 , the influence of that vowel is small [$t(8) = 1.19$], and at 200 msec before V_2 the mean difference across comparison pairs is negative, indicating that the influence of V_1 predominates.

Table 1. Mean Difference in Velar Position between /aC_ni/ and /iC_na/ Utterances. Taken at 50-msec Intervals before the (Acoustic) End of the Consonant String ($t=0$ msec)^a

	Comparison time (msec before V ₂)				
	(50)	100	150	200	250
Mean difference	116.3	78.8	45.7	-11.7	-62.7
t (8)	5.08	1.19	.78	.20	1.15
p	< .001	< .1	< .1	< .1	< .1

^a The difference is greatest at $t=50$ msec, where V₂ exerts the greater influence, and smallest at $t=250$ msec, where the influence of V₁ is greater.

C. The Model

This n -ary model of velar function postulates the segment-by-segment specification of both spatial and temporal parameters and permits the description both of the data presented here and of those already in the literature. It also generates hypotheses readily open to evaluation.⁴ This model requires the specification of at least four positional or movement goals, one each for nasal consonants, open vowels, close vowels, and obstruent consonants. Additional spatial goals may be required for half-close vowels and sonorant consonants; it should, on the other hand, be possible to specify velar position for nasal vowels as an interaction between the nasal consonant and the appropriate close or open vowel goals. Thus, velar position for nasalized close vowels is expected to be higher than that for nasalized open vowels.

The remaining differences in velar position, those resulting from coarticulatory interactions, would be accounted for with the temporal parameter, with the model positing that each successive velar goal is initiated some fixed time before the (acoustic onset of the) segment for which it is specified. The velar gesture is also assumed to end gradually, rather than abruptly, and to be completed some fixed time after the (acoustic) end of the segment for which it is specified. The model assumes that the velum is programmed to achieve its maximum excursion for a segment before the (acoustic) end of the segment. Once the velum has achieved this maximum displacement, it moves either toward its rest position or, possibly, some neutral, speech-ready position (see Chomsky & Halle, 1968). (It should be possible to determine whether or not this movement away from

⁴ Binary models are frequently proposed because of their simplicity. However, if a binary model requires a large number of reorganization instructions to account for observational data, it seems that an n -ary model may have equal, or even greater, elegance.

the maximum displacement is toward the rest position or the "neutral" position by comparing velar movement patterns just before marked junctural boundaries, where the neutral position might be expected, and in utterance-final positions, where the rest position would be expected.) The goal specification may take the form of movements toward and away from some spatial target position or, alternatively, simply of movements of greater or lesser extent. The present model is not able to distinguish between these two alternatives. In either case, however, the edges or "tails" of the successive goal specifications overlap, producing the coarticulatory effects commonly described.

The model predicts that the vowel following a consonant string will have greater influence on peak velar elevation than will a preceding vowel because the peak in the elevation function occurs late in the string; that is, closer to the second vowel (see Fig. 1). This prediction is, indeed, supported by the data offered above, where peak elevation is greater in /aC_ni/ than in /iC_na/ phrases. Similarly, velar position in the earlier portion of the consonant string is expected to be more heavily influenced by the first vowel, a prediction again supported by these data. Differences in velar position during nasal consonants would similarly be affected by the state values for adjacent segments, a hypothesis supported by the data of Bell-Berti *et al.* (1979).

The assumption of segments as the units of the motor program rests on several observations. First, the programmed unit is presumed to be no larger than a segment because velar elevation continues to increase through obstruent consonant strings of considerable length, and the peak elevation achieved is proportional to overall consonant duration. It seems unreasonable to assume that the velar goal for such strings is so much greater than would be necessary to prevent coupling that it is never reached. On the other hand, if one assumes a cumulative, segmental specification, this continuing elevation is to be expected.⁵ Second, peak velar elevation occurs at a nearly constant time before the end of the consonant string; that is, it does not occur earlier in longer strings, as might be expected if the goal for the following vowel, which is lower than that of the consonant string, begins to exert its influence. Finally, the second vowel begins to exert its influence at a relatively fixed time before its acoustic beginning. Thus, the beginning of the velar gesture for the vowel is linked to the beginning of other components of the vowel gesture

⁵ One would expect cumulative velar position as the response of an open-loop system. Such a system would obviate the need for continuous monitoring of velar position and, at the same time, guarantee velopharyngeal port closure adequate for preventing nasal coupling during oral segments.

itself and is not free to begin at different times in different phonetic sequences, as a feature-based model would predict. Instead, the beginning of the vowel gesture is expected to begin later in longer consonant strings (that is, later with reference to the beginning of the consonant string) than in shorter ones, and marked junctural boundaries would have the apparent effect of delaying "anticipation" because the segment being anticipated begins later, and thus its influence begins later.

It is important to note that this description of anticipation implies that it is the result both of temporally fixed relationships among the component gestures comprising a particular phonetic segment and of temporal overlap, or co-occurrence, of gestures for successive segments. These data do not permit determination of the effect of changes in lexical stress and in speaking rate on the timing of the beginning and end of the velar gesture in relation to the acoustic onset of the segment for which they are specified. Nor does this model contain hypotheses about the precise temporal relationships among the component gestures of a single phonetic segment. Thus, while it claims that a vowel begins to influence an immediately preceding consonant string about 150 to 200 msec before the acoustic onset of the vowel, it makes no claims about when the velar gesture begins in relation to the beginning of tongue-body movements for the vowel gesture, except to state that this relationship is constant for any given pattern of lexical stress and speaking rate.

Obviously, a complete model of velar function is not yet available. However, after the values for the temporal and spatial parameters have been established, it should be possible to extend the model to account for suprasegmental influences on velar position. Once this has been done, the model may be used to predict velar position in a wide variety of utterances to determine its validity.

VI. APPENDIX

A. Preliminaries: Oral Speech

Before considering the acoustic effects of adding the nasal resonator to the pharyngeal and oral resonators, it seems prudent to provide definitions and/or descriptions of concepts that will, of necessity, find their way into the following discussion. This treatment, of course, will not, and could not, be exhaustive.

Traditionally, in evolving an acoustic description of speech, the vocal tract has been viewed as an acoustic tube, one having variable shape and

length. For oral speech sounds, the tube is a simple one, having no side branches, with one end at the glottis and the other at the lips.⁶ For voiced oral speech sounds, the acoustic properties of such a tube can be described by its **transfer function**, which is the ratio of the volume velocity at the lips to that at the sound source (the glottis). The transfer function can be described by its **poles**, resonances which can be described by their frequencies and bandwidths, or **formants**. The resonance frequencies and their bandwidths are a function of the shape and length of the tube (Fant, 1971; Stevens & House, 1955, 1961). For voiceless speech sounds, the transfer function is the ratio of the volume velocity at the lips to the sound pressure at the source which, in this condition, is the aperiodic noise or transient excitation generated at the vocal tract constriction (Bell, Fujisaki, Heinz, Stevens, & House, 1961).⁷

B. The Effects of Nasal Coupling

Adding a side branch, or shunt, to the vocal tract tube increases the acoustic complexity of the system in several ways. Among them are the interactions of the poles and zeros (spectral minima) of the coupled system with those of the "simpler" system. For any given shape of the oral and pharyngeal branches, the transfer function of a system with a coupled side branch (e.g., nasal branch) is determined by the poles and zeros of the admittance (frequency-dependent susceptibility to flow across a boundary) into the three branches and the pressure gain across each branch (cf. Bell *et al.*, 1961).⁸ The pole frequencies of the nasal-branch driving-point admittance (the admittance into the nasal branch from the velar port) vary with the area of the port, increasing with increasing port size; the zeros remain fixed. Or, conversely, as the area of

⁶ This is an overly simplified view, to be sure. It is, however, a useful base for the following discussion. For examples of some of the additional considerations necessary to provide a thorough description, or prediction of the acoustic output of the vocal tract, the reader is referred to Fant (1971), Scully and Shirt (1979), and Stevens (1972).

⁷ A complete description of the acoustic output resulting from speech articulation also requires the specification of a **radiation function**, the ratio of the sound pressure some distance from the lips to the volume velocity at the lips (cf. Fant, 1971; Stevens & House, 1955).

⁸ An advance in understanding the interactions between coupled pharyngeal, oral, and nasal branches was effected by Mermelstein (Mermelstein, 1971; Rubin, Baer, & Mermelstein, 1979), who established a method for calculating the vocal tract transfer function based on the independence of the driving-point admittances looking into each branch from the velopharyngeal port and of the pressure gain across each branch. This has simplified the techniques necessary for calculating the coupled-system transfer function.

the port decreases, the pole frequencies of the nasal-branch driving-point admittance decrease, approach the frequencies of their paired zeros, and are canceled (Fujimura & Lindquist, 1971). The poles of the nasal-branch driving-point admittance are the frequencies at which zeros are observed in the transfer function of the vocal tract; therefore, the closer the pole frequencies of the nasal-branch admittance to the resonances of the rest of the vocal tract, the more extensive will be the effects of adding the nasal branch to the system.

In spite of this complexity, however, it is possible to describe, qualitatively, the results of some of the interactions among the oral, nasal, and pharyngeal resonators. (We will confine ourselves to the effects of nasal coupling on the transfer functions of vowels, and not nasal consonants, because of an interest in understanding observed differences in velar function for different vowels.) First, the lowest formant of the transfer function will fall between the lowest nasal-branch resonance frequency and the lowest formant of the corresponding nonnasalized vowel. More generally, the principal effects of nasal coupling occur in the frequency regions where the admittances into the oral-pharyngeal and nasal branches are most different, particularly in the region of F_1 . Nasal coupling also leads to a differential reduction, across vowels, in the amplitude, and an increase in the bandwidth of F_1 , and F_3 is minimized (cf. Fujimura & Lindquist, 1971; House & Stevens, 1956).

It has not yet been established, however, which one or group of these acoustic effects of nasal coupling has the greatest perceptual salience. Thus, while it is known that close vowels will be perceived as being nasalized at smaller velar port coupling areas than will open vowels (cf. Abramson, Nye, Henderson, & Marshall, 1979; House & Stevens, 1956), we do not know whether the perception of nasality results from amplitude or bandwidth changes, or increasing the center frequency of F_1 , or the presence of nasal resonances, or some combination of these or other acoustic results of coupling. Indeed, it may be that the relative positions or intensities of the lowest oral and nasal resonances in the transfer function cue the perception of nasality, especially for small coupling areas that do not have a great overall effect on the vowel spectrum.

Acknowledgments

The experiment reported here, and the preparation of this manuscript, were supported by NINCDS grants NS-13617 and NS-05332 and by BRSG grant RR-05596. The research was carried out at the Haskins Laboratories, whose staff and facilities made this work possible. I want to thank Katherine S. Harris and Patrick W. Nye for their thoughtful reading of the manuscript and very helpful suggestions. Finally, I especially want to thank Thomas Baer for his invaluable and tireless comments during the preparation of the manuscript.

References

- Abramson, A. S., Nye, P. W., Henderson, J., & Marshall, C. W. The perception of an oral-nasal continuum generated by articulatory synthesis. *Haskins Laboratories Status Report on Speech Research*, 1979, SR-57, 17-38.
- Azzam, N. A., & Kuehn, D. P. The morphology of musculus uvulae. *Cleft Palate Journal*, 1977, 14, 78-87.
- Bell, C. G., Fujisaki, H., Heinz, J. M., Stevens, K. N., & House, A. S. Reduction of speech spectra by analysis-by-synthesis techniques. *Journal of the Acoustical Society of America*, 1961, 33, 1725-1736.
- Bell-Berti, F. The velopharyngeal mechanism: An electromyographic study. *Haskins Laboratories Status Report on Speech Research*, 1973, Supplement, 1-159.
- Bell-Berti, F. Control of pharyngeal cavity size for English voiced and voiceless stops. *Journal of the Acoustical Society of America*, 1975, 57, 456-461.
- Bell-Berti, F. An electromyographic study of velopharyngeal function in speech. *Journal of Speech and Hearing Research*, 1976, 19, 225-240.
- Bell-Berti, F. The extent of a vowel's influence: Evidence from a study of velar function. In J. J. Wolf & D. H. Klatt (Eds.), *Speech communication papers presented at the 97th Meeting of the Acoustical Society of America*. New York: Acoustical Society of America, 1979. Pp. 79-82.
- Bell-Berti, F., Baer, T., Harris, K. S., & Niimi, S. Coarticulatory effects of vowel quality on velar elevation. *Phonetica*, 1979, 36, 187-193.
- Bell-Berti, F., & Hirose, H. Patterns of palatoglossus activity and their implications for speech organization. *Haskins Laboratories Status Report on Speech Research*, 1973, SR-34, 203-209.
- Bell-Berti, F., & Hirose, H. Palatal activity in voicing distinctions: A simultaneous fiberoptic and electromyographic study. *Journal of Phonetics*, 1975, 3, 69-74.
- Benguerel, A.-P., Hirose, H., Sawashima, M., & Ushijima, T. Velar coarticulation in French: An electromyographic study. *Journal of Phonetics*, 1977, 5, 159-167.
- Björk, L. Velopharyngeal function in connected speech. *Acta Radiologica*, 1961, Supplement 202.
- Bosma, J. F. A correlated study of the anatomy and motor activity of the upper pharynx by cadaver dissection and by animatic study of patients after maxillo-facial surgery. *Annals of Otolaryngology, Rhinology, and Laryngology*, 1953, 62, 51-72.
- Bronstein, A. J. *The pronunciation of American English*. New York: Appleton, 1961.
- Calnan, J. S. Modern view on Passavant's ridge. *British Journal of Plastic Surgery*, 1957, 10, 89-113.
- Carpenter, M. A., & Morris, H. L. A preliminary study of Passavant's Pad. *Cleft Palate Journal*, 1968, 5, 61-72.
- Chomsky, N., & Halle, M. *The sound pattern of English*. New York: Harper, 1968.
- Czermak, J. N. Ueber das Verhalten des Weichen Gaumens beim Hervorbringen der reinen Vocale. *Wiener Akademie Sitzungsberichte*, 1857, 27. Cited in Fritzell (1969).
- Czermak, J. N. Ueber reine und nasalierte Vocale. *Wiener Akademie Sitzungsberichte*, 1858, 28. Cited in Fritzell (1969).
- Czermak, J. N. Wesen und Bildung der Stimmund Sprachlaute. In *Czermak's gesammelte Schriften* (Vol. 2), Leipzig: Engelmann, 1869. Cited in Fritzell (1969).
- Dickson, D. R. Normal and cleft palate anatomy. *Cleft Palate Journal*, 1972, 9, 280-293.
- Dickson, D. R. Anatomy of the normal velopharyngeal mechanism. *Clinics in Plastic Surgery*, 1975, 2, 235-248.
- Dickson, D. R., & Maue-Dickson, W. Velopharyngeal anatomy. *Journal of Speech and Hearing Research*, 1972, 15, 372-381.

- Dickson, D. R., & Maue-Dickson, W. Velopharyngeal structure and function: A model for biomechanical analysis. In N. J. Lass (Ed.), *Speech and language: Advances in basic research and practice* (Vol. 3). New York: Academic Press, 1980. Pp. 167-222.
- Dixit, P., & MacNeilage, P. F. *Coarticulation of nasality: Evidence from Hindi*. Paper presented at the 83rd Meeting of the Acoustical Society of America, Buffalo, N. Y., April 1972.
- Fant, C. G. M. *Acoustic theory of speech production* (2nd ed.). The Hague: Mouton, 1971.
- Fritzell, B. The velopharyngeal muscles in speech: An electromyographic and cineradiographic study. *Acta Oto-laryngologica*, 1969, Supplement 250.
- Fujimura, O., & Lindquist, J. Sweep-tone measurements of vocal-tract characteristics. *Journal of the Acoustical Society of America*, 1971, 49, 541-558.
- Fujimura, O., Tatsumi, I. F., & Kagaya, R. Computational processing of palatographic patterns. *Journal of Phonetics*, 1973, 1, 47-54.
- Hagerty, R. F., & Hill, M. J. Pharyngeal wall and palatal movement in postoperative cleft palates and normal palates. *Journal of Speech and Hearing Research*, 1960, 3, 59-66.
- Hagerty, R. F., Hill, M. J., Pettit, H. S., & Kane, J. J. Posterior pharyngeal wall movement in normals. *Journal of Speech and Hearing Research*, 1958, 1, 203-210.
- Harrington, R. A study of the mechanics of velopharyngeal closure. *Journal of Speech and Hearing Disorders*, 1944, 9, 325-345.
- Harris, K. S., Schvey, M. M., & Lysaught, G. F. Component gestures in the production of oral and nasal labial stops. *Journal of the Acoustical Society of America*, 1962, 34, 743. (Abstract)
- Henke, W. L. *Dynamic articulatory model of speech production using computer simulation*. Unpublished doctoral dissertation, Massachusetts Institute of Technology, 1966.
- Honjo, I., Harada, H., & Kumazawa, T. Role of the levator palatini muscle in movement of the lateral pharyngeal wall. *Archives of Oto-Rhino-Laryngology*, 1976, 212, 93-98.
- House, A. S., & Stevens, K. N. Analog studies of the nasalization of vowels. *Journal of Speech and Hearing Disorders*, 1956, 21, 218-232.
- Isshiki, N., Honjow, I., & Morimoto, M. Effects of velopharyngeal incompetence upon speech. *Cleft Palate Journal*, 1968, 5, 297-310.
- Kent, R. D., Carney, P., & Severeid, L. R. Velar movement and timing: Evaluation of a model for binary control. *Journal of Speech and Hearing Research*, 1974, 17, 470-488.
- Kent, R. D., & Moll, K. L. Vocal-tract characteristics of the stop cognates. *Journal of the Acoustical Society of America*, 1969, 46, 1549-1555.
- Kozhevnikov, V. A., & Chistovich, L. A. *Rech: Artikulyatsiya, i vosprivatie*. Trans. as *Speech: Articulation and perception* (30.543). Washington, D.C.: Joint Publication Research Service, 1966. (Originally published, 1965.)
- Kuenzel, H. J. Reproducibility of electromyographic and velographic measurements of the velopharyngeal closure mechanism. *Journal of Phonetics*, 1978, 6, 345-352.
- Leutenegger, R. R. *The sounds of American English*. Chicago: Scott, Foresman, 1963.
- Lindblom, B. Spectrographic study of vowel reduction. *Journal of the Acoustical Society of America*, 1963, 35, 1773-1781.
- Lubker, J. F. An electromyographic-cineradiographic investigation of velar function during normal speech production. *Cleft Palate Journal*, 1968, 5, 1-18.
- Lubker, J. F., Fritzell, B., & Lindquist, J. Velopharyngeal function: An electromyographic study. Quarterly Progress and Status Report (*Speech Transmission Laboratory, Royal Institute of Technology, Stockholm*), 1970, 4, 9-20.
- Lubker, J. F., Lindquist, J., & Fritzell, B. *Some temporal characteristics of velopharyngeal muscle function*. Paper presented at the Phonetics Symposium, University of Essex Language Center, May 1972.

- Lubker, J. F., & May, K. Palatoglossus function in normal speech—Electromyographic implications. *Journal of the Acoustical Society of America*, 1973, 53, 296. (Abstract)
- McClellan, M. Forward coarticulation of velar movement at marked junctural boundaries. *Journal of Speech and Hearing Research*, 1973, 16, 286–296.
- Mermelstein, P. Calculations of the vocal-tract transfer function for speech synthesis applications. *Proceedings of the Seventh International Congress on Acoustics, Budapest*, 1971, 3, 173–176.
- Minifie, F. D., Abbs, J. H., Tarlow, A., & Kwaterski, M. EMG activity within the pharynx during speech production. *Journal of Speech and Hearing Research*, 1974, 17, 497–504.
- Minifie, F. D., Hixon, T. J., Kelsey, A. A., & Woodhouse, R. J. Lateral pharyngeal wall movement during speech production. *Journal of Speech and Hearing Research*, 1970, 13, 584–594.
- Moll, K. L. Velopharyngeal closure on vowels. *Journal of Speech and Hearing Research*, 1962, 5, 30–77.
- Moll, K. L., & Daniloff, R. G. Investigation of the timing of velar movements during speech. *Journal of the Acoustical Society of America*, 1971, 50, 678–684.
- Moll, K. L., & Shriner, T. H. Preliminary investigation of a new concept of velar activity during speech. *Cleft Palate Journal*, 1967, 4, 58–69.
- Niimi, S., Bell-Berti, F., & Harris, K. S. Dynamic aspects of velopharyngeal closure. *Haskins Laboratories Status Report on Speech Research*, 1978, SR-55/56, 45–62.
- Nylen, B. O. Cleft palate and speech. *Acta Radiologica*, 1961, Supplement 203.
- Ohala, J. J. Monitoring soft palate movements in speech. *Project on Linguistic Analysis Reports (Phonology Laboratory, Department of Linguistics, University of California, Berkeley)*, 1971, 13, JO1–JO15.
- Passavant, G. *Ueber die Verschlussung des Schlundes beim Sprechen*. Frankfurt a.M.: J. D. Sauerländer, 1863. Cited in Fritzell (1969).
- Perkell, J. S. *Physiology of speech production: Results and implications of a quantitative cineradiographic study*. Cambridge, Mass.: MIT Press, 1969.
- Rubin, P., Baer, T., & Mermelstein, P. An articulatory synthesizer for perceptual research. *Haskins Laboratories Status Report on Speech Research*, 1979, SR-57, 1–16.
- Scully, C., & Shirt, M. A. Oral and nasal outputs for vowels in non-nasal contexts. *Proceeding of the Ninth International Congress of Phonetic Sciences*, 1979, 1, Institute of Phonetics, University of Copenhagen, 212.
- Shprintzen, R. J., Lencione, R. M., McCall, G. N., & Skolnick, M. L. A three dimensional cinefluorographic analysis of velopharyngeal closure during speech and nonspeech activities in normals. *Cleft Palate Journal*, 1974, 11, 412–428.
- Skolnick, M. L. Video velopharyngography in patients with nasal speech, with emphasis on lateral pharyngeal wall motion in velopharyngeal closure. *Radiology*, 1969, 93, 747–755.
- Skolnick, M. L., McCall, G. N., & Barnes, M. The sphincteric mechanism of velopharyngeal closure. *Cleft Palate Journal*, 1973, 10, 286–305.
- Stevens, K. N. The quantal nature of speech: Evidence from articulatory-acoustic data. In E. E. David & P. B. Denes (Eds.), *Human communication: A unified view*. New York: McGraw-Hill, 1972. Pp. 51–66.
- Stevens, K. N., & House, A. S. Development of a quantitative description of vowel articulation. *Journal of the Acoustical Society of America*, 1955, 27, 484–493.
- Stevens, K. N., & House, A. S. An acoustical theory of vowel production and some of its implications. *Journal of Speech and Hearing Research*, 1961, 4, 303–320.
- Stevens, K. N., & House, A. S. Perturbation of vowel articulation by consonantal context: An acoustical study. *Journal of Speech and Hearing Research*, 1963, 6, 111–128.

- Subtelny, J. D., Koepf-Baker, H., & Subtelny, J. D. Palatal function and cleft palate speech. *Journal of Speech and Hearing Disorders*, 1961, 26, 213-224.
- Ushijima, T., & Hirose, H. Electromyographic study of the velum during speech. *Journal of Phonetics*, 1974, 2, 315-326.
- Ushijima, T., & Sawashima, M. Fiberscopic observation of velar movements during speech. *Annual Bulletin (Research Institute of Logopedics and Phoniatrics, University of Tokyo)*, 1972, 6, 25-38.
- van den Berg, J. Myoelastic-aerodynamic theory of voice production. *Journal of Speech and Hearing Research*, 1958, 1, 227-244.
- Warren, D. Nasal emission of air and velopharyngeal function. *Cleft Palate Journal*, 1967, 4, 148-156.
- Zagzebski, J. A. Ultrasonic measurement of lateral pharyngeal wall motion at two levels in the vocal tract. *Journal of Speech and Hearing Research*, 1975, 18, 308-318.