

UNDERSTANDING VELIC MOTOR CONTROL: STUDIES OF SEGMENTAL CONTEXT

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1. INTRODUCTION

Linguistically (i.e., phonologically), the velopharyngeal mechanism is required only to provide a binary distinction between nasal and oral segments. Physiologically, however, the velopharyngeal mechanism system is required to function in such a way as to provide sufficient closure of the velic port to prevent acoustic and aerodynamic coupling of the nasal and oral tracts for the production of oral segments and to enhance acoustic coupling for nasal segments. That is, the velopharyngeal port must be effectively closed for oral phonemes and effectively open for nasal phonemes, and this may require more than two velic position values.

As the articles in this volume attest, researchers from a number of fields have been concerned with describing the nature of oral/nasal articulatory behaviors, motivated by questions of linguistic intent and by the need for clinical tools for evaluating and treating persons with anomalous or otherwise malfunctioning articulatory mechanisms. Questions of how segmental articulatory behaviors are influenced by the articulation of other segments have been addressed by researchers interested in discovering how the speech motor system organizes its output. Observations made during the nineteenth century of velic and posterior pharyn-

geal wall displacements and velopharyngeal port size (see, for example, Brücke, 1856; Czermak, 1869; Passavant, 1863) have developed into two distinct lines of study of velopharyngeal function. Some investigators have been concerned with how the velopharyngeal mechanism is used to produce distinctively oral and nasal segments—that is, with the intrasegmental organization of the articulators marshalled to produce fluent speech. Others have been concerned with differences in velopharyngeal activity that reflect the temporal and spatial organization of successive speech gestures—that is, the intersegmental interactions due to phonetic context that include, but are not limited to, coarticulation.

Because the velum is responsible for realizing a binary phonological distinction, many investigators interested in understanding velic function have incorrectly treated the velum as if it had only two phonetic-level possibilities (“gestures”) in languages without contrastive vowel nasality: raised for oral consonantal segments and lowered for nasal ones, with velic position for vowels inherently neutral and determined by consonantal environment. Furthermore, since the data of many studies are drawn only from nasal contexts, it is very difficult to separate the intra- and intersegmental functions of the velum. Supporting the view of the velopharyngeal mechanism as having a control system with more than two values is a long series of studies of velopharyngeal function in speech, studies that have revealed the following characteristics of velopharyngeal function. First, velum position is lowest for nasal consonants, being somewhat higher for nasal vowels than nasal consonants (see Henderson, 1984). Second, velum position is higher for high vowels than for low vowels (e.g., Passavant, 1863), and its position for mid vowels is somewhat higher than the position for low vowels (Henderson 1984). Third, the velum is higher for obstruent consonants than for high vowels (e.g., Bell-Berti, 1980).

The problem of separating the intra- and intersegmental functions of the velum is further compounded by the almost constantly changing spatial relationships among the articulators that are observed within the vocal tract during speech. Indeed, the common observation that any given articulator holds a constant position for only a very brief time, if at all, finds support in a number of studies showing essentially continuous changes in velic position even during sequences of oral segments (e.g., Bell-Berti, 1980; Bell-Berti, Baer, Harris, & Niimi, 1979; Bell-Berti & Krakow, 1991a). When nasal segments are added, distinguishing velic position for the oral vowels from the coarticulatory influences of the nasal segments can be achieved only with utmost care. Thus, we must reconsider interpretations of data used in developing models of velic function drawn from studies of nasal coarticulation whose designs are based on assumptions of binary phonetic-level velic activity (e.g., Kent, Carney, & Severeid, 1974; Moll & Daniloff, 1971; Ohala, 1971). Finally, a complete description of velic motor control also requires that we examine the effects on velic position of a segment’s syllable position and syllable stress (Krakow, 1987, 1989, this volume; Vaissière, 1988), as well as its

position within a phrase or sentence (Bell-Berti & Krakow, 1991b; Krakow, this volume).

2. VELOPHARYNGEAL PORT ADJUSTMENTS

2.1. Muscular Force

There are a number of factors whose action may affect velic elevation and velopharyngeal port size. These include activity of the levator veli palatini and superior pharyngeal constrictor muscles (Bell-Berti, 1973, 1976; Fritzell, 1969; Lubker, 1968), as well as activity of the palatoglossus muscle (Fritzell, 1969; Lubker, 1968; Lubker, Fritzell, & Lindqvist, 1970), and biomechanical forces exerted by the tongue pulling downward on the velum through the anterior faucial pillar and palatoglossus muscles (Moll & Shriner, 1967). The muscular activity of this region has been studied for some time and has been described extensively elsewhere (see Dickson & Maue-Dickson, 1980, for a comprehensive review); thus it is discussed here only briefly. However, several studies have increased our understanding of (or added to our recognition that we do not yet understand) the forces and control mechanisms involved in velopharyngeal function, and they are reviewed here in more detail.

2.1.1. CLOSING THE VELOPHARYNGEAL PORT

2.1.1.1. Levator Veli Palatini. The levator palatini muscle is widely accepted as the muscle primarily responsible for closing the velopharyngeal port by exerting an upward and backward pull on the velum (e.g., Bell-Berti, 1973, 1976; Bosma, 1953; Dickson, 1975; Fritzell, 1969; Lubker, 1968). In electromyographic-cineradiographic studies of velic function, Lubker (1968) and Fritzell (1969) found high correlations (approximately .80) between the strength of levator palatini activity and velic position, as did Bell-Berti and Hirose (1975), who reported a correlation coefficient of .84 between levator palatini activity and velic position in their electromyographic-fiberoptic study. These authors have concluded that levator palatini activity is primarily responsible for the observed differences in velic position across an utterance.

However, questions have been raised about the extent to which velic position is under voluntary control and how such control may be related to observed differences in velic position for different segments. In a study of voluntary nonspeech velic positioning, Shelton, Harris, Scholes, and Dooley (1970) found that when asked to produce seven different velic positions, their two subjects were at best able to produce only two ranges of velic position. They concluded that subjects

are able to learn to position the velum voluntarily, although such movements are considerably less precise than finger movements obtained in comparable situations. From this they postulated that speakers have sensory, probably kinesthetic, information available about velic position. The source of this kinesthetic information, however, is still uncertain, since Kuehn, Templeton, and Maynard (1990) and Liss (1990) have reported conflicting results from histological examinations of levator palatini, with Kuehn et al. reporting an absence of muscle spindles in levator palatini and Liss reporting their presence. (Both studies did find muscle spindles in the palatoglossus muscle.)

Questions have also been raised about the speed with which velopharyngeal closure can be achieved, the velum often being described as a "sluggish" articulator. Clearly, knowing the response time of the velum will aid our interpretation of data collected toward the goal of determining the temporal domain of velic gestures. There are data suggesting that velic movements for speech produced at a subject's comfortable speaking rate begin about 250 msec before the acoustic events for which they are required, provided they will not distort intervening segments (Bell-Berti, 1980; Bell-Berti & Krakow, 1991a). Recently, Dalston and Keefe (1988) reported the results of a reaction time study in which subjects were asked to produce /m/ in response to a ready tone, and then /pi/ as quickly as possible in response to an imperative tone. They measured the interval between presentation of the imperative tone and velopharyngeal closure (as reflected in the output of a photodetector placed across the velopharyngeal port from a light source positioned below the velum). Dalston and Keefe reported velic reaction times of about 200 msec, which were not different from the labial and digital reaction times they reported and led them to conclude that the velum is not inherently slower than other articulators. Although Dalston and Seaver (1990) reported somewhat longer velic reaction times (224 msec to consonant onset, 280 msec to velopharyngeal port closure), their results are within the range of values reported by Bell-Berti (1980) and Bell-Berti & Krakow (1991a). These data are especially relevant when we are interpreting the data collected in studies of anticipatory nasal coarticulation. And, there are some data suggesting that speaking rate effects on velic movements have little effect on the timing of those movements, but rather affect their temporal overlap. However, more data from additional speakers are necessary to allow us to confirm or modify this conclusion.

2.1.1.2. Superior Pharyngeal Constrictor. There is still controversy about the role of the pars pterygopharyngea of the superior pharyngeal constrictor muscle, whose contraction has been posited to aid in velopharyngeal port closure by drawing the lateral and posterior pharyngeal walls inward with a purse-string motion (Fritzell, 1969; Lubker, 1968; Skolnick, McCall, & Barnes, 1973). Some studies have suggested that the observed lateral and posterior pharyngeal wall movements

ascribed to superior pharyngeal constrictor contraction are actually the result of levator palatini activity (Bosma, 1953; Dickson, 1975; Dickson & Maue-Dickson, 1972; Honjo, Harada, & Kumazawa, 1976; Niimi, Bell-Berti, & Harris, 1982). There is, on the other hand, evidence that the lateral pharyngeal wall movements occurring at and just below the level of velopharyngeal port closure are not correlated with velic height and, consequently, are not attributable to levator palatini action (Iglesias, Kuehn, & Morris, 1980). There is general agreement, however, that the superior and middle pharyngeal constrictors are responsible for some of the lateral pharyngeal wall movement observed in the oropharynx for open vowel articulations (Bell-Berti, 1973, 1976; Minifie, Hixon, Kelsey, & Woodhouse, 1970; Zagzebski, 1975).

2.1.2. OPENING THE VELOPHARYNGEAL PORT: PALATOGLOSSUS ACTIVITY

There have been two contrasting hypotheses as to how the velopharyngeal port is opened for nasal articulation: (1) it is opened by the increased activity of some muscles or group of muscles (the "gate-pull" model of Lubker et al., 1970), or (2) it is opened passively, as the result of relaxation of the muscles that close it, especially levator palatini (as proposed, for example, by Bell-Berti, 1973, 1976). In electromyographic studies of the velopharyngeal region, Fritzell (1969) and Lubker et al. (1970) concluded that the velopharyngeal port is opened by relaxation of levator palatini activity and a concurrent increase in palatoglossus activity. On the other hand, Bell-Berti (1973, 1976) and Bell-Berti & Hirose (1973) found no evidence of increased palatoglossus activity coincident with the decrease in levator palatini activity observed for velopharyngeal port opening. Rather, they found palatoglossus activity to be associated with vowel and velar consonant articulation and concluded that the universal "nasalizing" mechanism involves relaxation of the levator palatini, and that although the possibility that some speakers may use the palatoglossus in velar lowering remains, such a mechanism is not universal.

However, these earlier studies of velopharyngeal port opening have focused on languages in which vowel nasality is not distinctive, leaving open the possibility that palatoglossus activity may play an important role in velopharyngeal port opening for phonemically nasal vowels (especially in oral consonant environments when substantial and rapid velopharyngeal port opening is necessary to assure nasal coupling) and for nasal consonants in the environment of phonemically oral vowels (which, according to this view, must resist nasality assimilation to maintain the vocalic contrast). Recently, though, in electromyographic studies of Hindi, a language that has phonemically contrastive oral and nasal vowels, Dixit has shown that palatoglossus activity is primarily associated with tongue-body movements (Dixit, 1991; Dixit, Bell-Berti, & Harris, 1987).

2.2. Acoustic Requirements

The production of perceptually appropriate nasal/oral segment distinctions requires that a speaker manipulate the size of the velopharyngeal port either to prevent or to enhance the acoustic and aerodynamic coupling of the nasal tract to the oropharyngeal tract (House & Stevens, 1956). For oral segments, this means that the area of the port must only be sufficiently small that the nasal cavities will not be acoustically coupled to the oral cavity and that nasal airflow will be sufficiently small that no audible turbulence will occur in the nasal cavities, *not* that the velopharyngeal port must be completely closed for successful oral articulation to occur. If one turns to the speech production literature, one finds a number of reports (Bjork, 1961; Warren, 1979) of speech produced by normal speakers (and perceived as normal) in which some oral segments were produced with small velopharyngeal port openings (up to 5 mm²). Furthermore, an extensive series of studies of cleft palate speakers has led to the conclusion that speakers who are able to achieve minimum velopharyngeal port areas of 20 mm² are able to build up intraoral pressures adequate to the production of plosive and fricative consonants (Dalston, Warren, Morr, & Smith, 1988; Warren, 1964, 1967, 1986; Warren & Devereaux, 1966; Warren & Ryon, 1967). Thus, we may conclude that, so long as the area of the velopharyngeal port is no greater than about 20 mm², perceptually oral segments may be produced.

3. SEGMENTAL EFFECTS

3.1. Segment Identity

Velic position is more varied than one would expect from merely considering the binary distinction between [+nasal] and [-nasal]. For example, the earliest reports of velic articulation demonstrating such variations, published in the nineteenth century, showed that velic position varied directly with vowel height (Brücke, 1856; Czermak, 1869; Passavant, 1863). Subsequent studies have reconfirmed that there are differences in velic position for oral vowels of different heights (e.g., Bell-Berti et al., 1979; Fritzell, 1969; Henderson, 1984; Lubker, 1968; Moll, 1962; Moll & Shriner, 1967) and have added substantially to our descriptions of velic function in speech.

3.1.1. VOWELS

The direct relationship between velic position and oral vowel height that was originally described more than a century ago has been confirmed and refined by a number of more recent studies and will be reviewed here in only an abbreviated

form. First, velic position is lowest for nasal consonants, somewhat higher for low vowels, higher still for high vowels, and highest for obstruent consonants. In context, velic position for oral vowels varies directly with vowel height in nasal as well as oral environments (Bell-Berti et al., 1979; Henderson, 1984); furthermore, velic position is lower for (phonemically) oral vowels between obstruent consonants than for the consonants themselves (Bell-Berti, 1980; Bell-Berti et al., 1979; Henderson, 1984; Karnell, Linville, & Edwards, 1988; Ushijima and Sawashima, 1972). Finally, we know that velic position for phonemically nasal vowels varies with vowel height just as it does for oral vowels, albeit through a narrowed range of substantially lower velic positions than for oral vowels (Henderson, 1984).

The differences in velic position between high and low vowels have been attributed to two factors. The first of these is the differences in the strength of levator palatini contraction raising the velum that are reflected in levator palatini electromyographic potentials (Bell-Berti, 1973, 1976; Fritzell, 1969; Lubker, 1968; Moll & Shriner, 1967). The second factor is the downward pull of palatoglossus that occurs as a result of its contraction to narrow the faucial isthmus for open vowels (Bell-Berti, 1973, 1976) and its resistance to being stretched during the articulation of low vowels (Moll & Shriner, 1967). More recently, though, Kuehn, Folkins, and Cutting (1982) studied the relation between levator palatini electromyographic (EMG) activity and velic positions in productions of sustained /s/, /i/, /u/, [a], and [ã] and failed to reveal a stable pattern between these measures, although they did report stable relationships between levator palatini and palatoglossus and/or palatopharyngeus EMG activity. A final resolution of this discrepancy awaits further study, including research into the ways that muscle activity varies to produce the continuously changing positions characteristic of speech as compared with the achievement and maintenance of static positions.

One final point about velic positions for vowel articulations: early acoustic modeling studies (e.g., House & Stevens, 1956) showed that, for a given velopharyngeal port area, acoustical coupling is more likely to occur with high than with low vowels. More recently, Maeda (this volume) has described the interaction of the nasal poles and zeros with oral tract vowel formants, explaining the different effects on different vowels that result from the same changes in velopharyngeal port area. Moreover, Rochet and Rochet (1991), in an acoustic study of nasal assimilation, have reported that high oral vowels in nasal consonant environments are nasalized through a greater part of their durations (both proportionally and absolutely) than are low oral vowels produced in the same environments. The Rochets' data, together with reports that [i] is perceived as being nasalized at smaller velic port areas than [a] (Maeda, this volume; Bell-Berti & Baer, 1983), support the view that the observed differences in velic positions for oral vowels (in oral environments) are the result of speakers' intentions to produce high vowels with sufficiently smaller velar port areas than they use for low vowels and thus to avoid inappropriate nasal coupling. One caveat, though: although speakers of

different languages may provide the same oral and nasal identifications of a set of vowels, the listeners' judgments of the naturalness of those vowels, as well as their discrimination of those vowels, may differ in language-specific ways, indicating that there is more to the distinction than velic position and port area (see Beddor, this volume, for a comprehensive discussion of this issue).

3.1.2. CONSONANTS

In addition to varying with consonantal nasality and orality, velic position also varies with different values of the consonantal features of manner of articulation, place of articulation, and voicing. Thus, the long-held belief that velic position is lower for liquids than for obstruent consonants has found support in the research literature. For example, Moll and Daniloff (1971) have reported that velic lowering in anticipation of a nasal consonant could take place during the production of /l/, and Bell-Berti and Krakow (1991a) found velic position for /l/ (in oral intervocalic positions) to be more like that for vowels than for obstruent consonants. On the other hand, though, there are many reports of increases in velic position for obstruents in intervocalic contexts (e.g., Bell-Berti & Hirose, 1975; Bell-Berti et al., 1979; Bjork, 1961; Karnell et al., 1988).

Results of studies of the effect of place of articulation on velic position for consonants with oral cavity constrictions seem more complicated than those for manner of articulation.¹ For example, in a study of nasal consonant articulation, Keefe and Dalston (1989) reported generally faster velopharyngeal port opening gestures and slower velopharyngeal port closing gestures for /n/ than for /m/ and /ŋ/. These results may be confounded, though, by the unequal distribution of pre- and postvocalic contexts for the three nasal consonants: /m/ and /ŋ/ occurred only postvocalically, whereas two of the five /n/ contexts were prevocalic. These contextual differences may be a problem in light of Krakow's (1989) report showing that syllable-final nasals are produced with lower minimum velic positions (and lowering and raising gestures of greater amplitude) than syllable-initial nasals. Furthermore, and in contrast with Keefe and Dalston's (1989) data on the effects of place of articulation, there are EMG data showing the same patterns of levator palatini suppression for bilabial and velar nasal consonants (Bell-Berti, 1973). Finally, there are EMG data suggesting that place of articulation has little effect on the actions of the muscles primarily responsible for effecting velic position and port closure (levator palatini and superior constrictor) for oral stops whose primary constrictions occur in front of the velic port (Bell-Berti, 1973; Bell-Berti & Hirose, 1973), although there are place of articulation effects on palatoglossus activity for oral stop articulations (see Section 2.1). We may infer from these data that velic position is affected only indirectly by place of articulation, through the mechanical force exerted by the palatoglossus on the velum as it aids in approximating the tongue dorsum and velum for velar stop and nasal consonants.

Finally, velic position has also been shown to contribute to the pharyngeal cavity volume adjustments necessary to maintain voicing for obstruent consonants. So, for example, Bell-Berti (1975; Bell-Berti et al., 1979) has shown that some speakers increase vertical displacement of the velum for voiced obstruents, presumably to increase pharyngeal cavity volume (and thus decrease intra-oral pressure) to maintain the transglottal pressure difference necessary to maintain glottal pulsing (see also Rothenberg, 1968; Kent & Moll, 1969). Bell-Berti (1975) also reported that other speakers may use a lower velic position, presumably to allow the nasal escape of air, again to foster the transglottal pressure difference necessary to maintain glottal pulsing during a stop occlusion, in agreement with the report of Yanagihara and Hyde (1966) that the beginning of voiced stop occlusions may be accompanied by some air leakage.

3.2. Coarticulation

Coarticulation, or the influence of the articulatory needs of one phonetic segment on the articulation of nearby segments (see, e.g., Daniloff & Hammarberg, 1973), has been studied with the expectation that it will shed light on the nature of the organizational units of speech production. The nature of these units has been much discussed for many years, largely as the result of our failure to have identified invariant articulatory behaviors associated with the phonemic units of language, a failure that flies in the face of our intuitions that speech is structured segmentally. In general, the focus of coarticulation studies has been anticipatory, rather than carryover, coarticulation, since the consensus has been that anticipatory coarticulation reflects reorganization of the motor system for segmental articulations, while carryover coarticulation has usually been attributed to mechanical and inertial forces acting on the articulators (e.g., Lindblom, 1963; MacNeilage, 1970), even though, as Daniloff and Hammarberg (1973) point out, there is substantial evidence that carryover must be deliberate, since its effects are large at slow speaking rates. These differing views of the nature of anticipatory and carryover coarticulation highlight the critical question in coarticulation: Do all the articulatory patterns that have been identified as coarticulation arise from the same types of interactions (i.e., are coarticulatory effects a homogeneous or heterogeneous group of phenomena)?

In considering the results of their studies of coarticulation, different researchers have developed different theories about the nature of coarticulation. Generally, these theories fall into two groups, "feature spread" and "coproduction" explanations, and each group of theories is supported by some of the reported data. Briefly, the earliest studies led to the development of feature spread theories (e.g., Henke, 1966; Kozhevnikov and Chistovich, 1966), in which feature values of earlier segments are presumed to take on those of later ones, so long as such a change does not impede the articulation of the earlier segments. For example, nasal coar-

tication will be blocked by the requirements of obstruent production but not by those of vowels (in languages without contrastive vowel nasality). Inherent in these theories is a view of speech as a series of beads on a string, with segments being composed of bundles of articulatory features whose individual (phonetic) values may be unspecified for some segments (see, for example, Keating 1988a, 1988b). In these theories the articulatory features of each segment are expected to be realized simultaneously in the absence of coarticulatory possibilities (i.e., if the production of adjacent segments would be impeded by the "spread" of feature values). In contrast with feature spread theories, coproduction theories propose that the realization of the features of a segment is synchronous, though not simultaneous (Bell-Berti & Harris, 1981; Browman & Goldstein, 1986; Fowler, 1980; Saltzman & Munhall, 1989). In these theories, the articulatory components of a segment (i.e., the segment's "core structure") are presumed to begin before and to end after the acoustic period in which they are dominant, and the onsets and offsets of the different components vary by articulator. Coproduction interpretations explain coarticulatory effects as the result of the overlapping, and consequent addition, in the absence of conflicting articulatory requirements, of these articulatory "tails" (onsets and offsets) with the core structures of neighboring segments, rather than of changes in the phonetic values of segmental specifications. Coproduction theories also propose that such interactions occur only over a relatively short time, although the timing may vary across articulators to the extent that different articulators have different onsets and offsets. That is, coproduction models propose that the nature of a segment's core structure does not change, but that its realization may *appear* to change as it overlaps more and less with the onsets and offsets of other segments.

In order to be able to identify the maximum extent of coarticulation, many studies of coarticulation have focused on the lips or velum, on the assumption that these articulators have comparatively simple articulatory dimensions and specifications and that they are thus relatively free to vary under pressures from adjacent segments: the behaviors of these articulators are expected to be the best possible reflectors of the potential extent of coarticulatory interactions, as well as of the linguistic and physiological factors that limit it. However, the extensive evidence of multivalued velic position specification described above (in Section 2.1 and also in Krakow, this volume) makes the acceptability of the underspecification assumption for velic function untenable. And since velic articulatory patterns cannot be accounted for by a description that supposes only a binary specification of velic activity, we must thoroughly reexamine those theories and data for which the underspecification assumption was made.

Happily, once we accept that velic behavior is more complex than often assumed, we find that many reported conflicts in the data are more apparent than real. For example, several studies of anticipatory nasal coarticulation cited in support of various feature spread models have examined the timing of velar lowering

during various segment sequences preceding a nasal consonant and reported the anticipation of nasality to begin as many as three to six segments before the nasal consonant. The problem with these studies has been the general failure to consider that some of the observed velic movements were associated with the articulation of the vocalic and liquid segments preceding the nasal consonant, rather than attributing them entirely to the downstream nasal segment (e.g., Bladon & Al-Bamerni, 1982; Kent et al., 1974; McClean, 1973; Moll & Daniloff, 1971). That is, the designs of the studies were based on the acceptance of a phonologically based description of the feature [nasal] (for the languages studied) as having only three values, [-] for obstruent consonants, [+] for nasal consonants, and an unspecified, or neutral, value (i.e., [0]) for all other segments (i.e., vowels and liquids), as an accurate representation of the phonetic specification of those segments (for a more complete discussion of this issue, see Boyce, Krakow, & Bell-Berti, 1991). The problem that resulted directly from accepting this phonetic-level specification was that many studies failed to use minimally contrastive utterances (in which the vocalic sequence preceded an oral consonant). Indeed, even using less perfect controls like *Free Ottawa* as a control for *Free Ontario* (Moll & Daniloff, 1970) or *He asked* as a control for *He answered* (Kent et al., 1974), to assure that lowering attributed to the nasal consonant was all actually due to the nasal consonant, would make interpretation of the results more straightforward. Furthermore, details of the patterns of velic lowering were not addressed; rather, the earliest moment at which velic lowering occurred was identified as the beginning of anticipation of the nasal consonant. In fact, though, when one examines the velic lowering pattern, one observes, as Benguerel, Hirose, Sawashima, and Ushijima (1977a) have noted, that there is velic lowering for the vowels followed by velic lowering for the nasal consonant (the latter starting near the beginning of the vowel immediately preceding the nasal consonant).

An alternative to feature spread theories is provided by the coproduction theories that posit simple overlapping of segmental gesture onsets with gestures of neighboring segments as the source of most coarticulatory phenomena. For example, the coproduction model of Bell-Berti and Harris (1981) proposes, first, that the articulatory period of a segment naturally extends beyond the acoustic period dominated by that segment; second, within-segment articulatory periods for different articulators may, and probably do, begin at different (but synchronized) times in relation to the segment's acoustic period; and third, in the absence of articulatory conflict, the articulatory period for a given articulator begins at a relatively constant time before the segment's acoustic period. In relation to velic coarticulation, the Bell-Berti and Harris theory predicts that velic movements will begin when the onset of the velic component of one segment's core gesture overlaps all or part of the acoustic period and/or offset of other segments' core gestures, provided that the outcome will not be distorted by the resulting addition of gestures.

In order to test the ability of coproduction theories to account for the data of velic coarticulation studies, we will examine in detail some of the predictions of velic movement patterns made by the Bell-Berti and Harris model (Figure 1); these predictions assume that velic gesture specification is *n*-ary (that, e.g., there are specific velic gestural values for obstruents, liquids, and high oral vowels, low

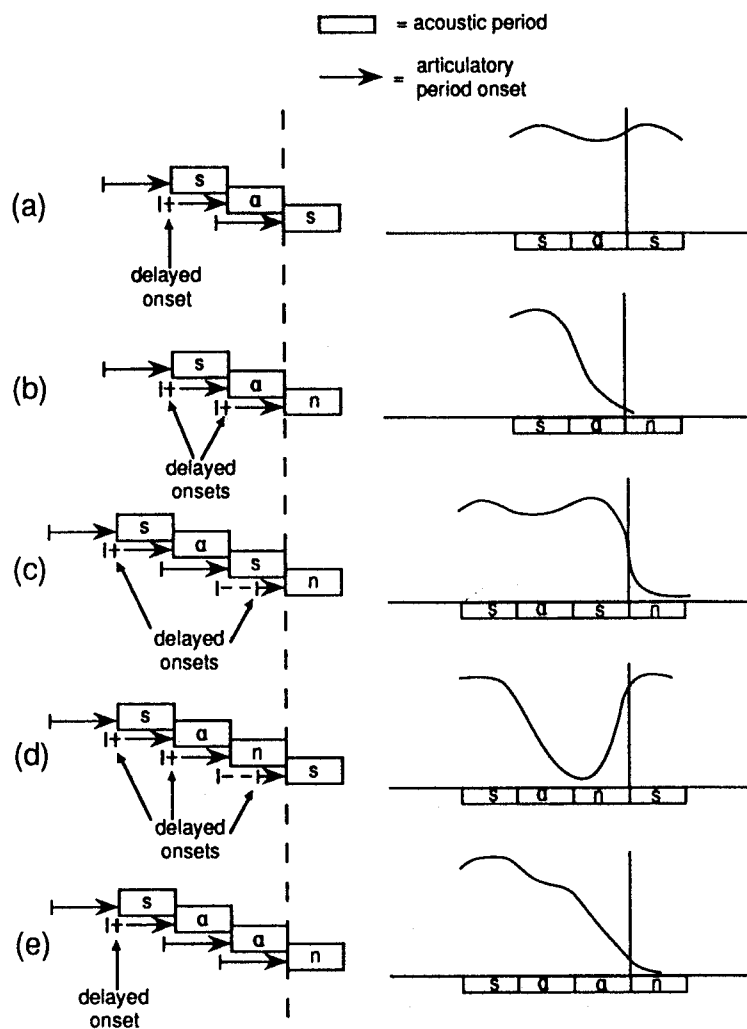


Figure 1. Predictions of velic movement patterns for five sequences (based on the coproduction model of Bell-Berti & Harris, 1981). This set includes one example (c) in which a syllable boundary falls within a consonant sequence.

oral vowels, high nasal vowels, low nasal vowels, and nasal consonants). Although the examples shown in Figure 1 contain only the segments [s], [a], and [n], the predictions of the model are the same for $C = \text{any voiceless obstruent consonant}$, $V = \text{any low oral vowel}$, and $N = \text{any nasal consonant}$. For simplicity's sake, in this schematic representation all segments are of the same duration (i.e., have the same horizontal length). Furthermore, only timing relationships are represented on the left-hand side of the figure—neither the direction nor the amplitude of displacement of the velic gestures is represented in the figure.

The first prediction of this model is that, in C_1VC_2 syllables, velic lowering for V will begin toward the middle or end of the acoustic period of C_1 (depending upon the duration of C_1), with its lowering onset delayed long enough for adequate velopharyngeal closure to be achieved for C_1 , and velic raising will begin for C_2 during the acoustic period for V (see Figure 1a). This is an example of true coarticulation—in this case carryover coarticulation—in which the velic gesture for a downstream segment (V) is modified by the requirements of an earlier segment (C_1). The second prediction is that, in C_1VN syllables, velic lowering for V will, again, begin toward the middle or end of the acoustic period of C_1 , but velic lowering for N will not begin until the end of the acoustic period of C_1 (or the onset of V), because substantial lowering during C_1 would result in its distortion (Figure 1b). That is, if the obstruent, C_1 , would be distorted by the onset of velic lowering (at the time that the articulatory period for the nasal consonant's velic gesture would naturally begin), that onset will be suppressed until its expression will not result in distortion. This is another example of carryover coarticulation, in which the velic gesture for a downstream segment (N) is reorganized (by delaying the onset of its expression) because of the requirements of an earlier segment (C_1). Furthermore, since the lowering gesture for N may begin at the beginning of the acoustic period for V without distorting V (in a language without contrastive vowel nasality), the separate but overlapping gestures for V and N are coproduced (added) and are realized as a single downward movement.

The third and fourth predictions of this model are for $C_1VC_2N \dots$ and $C_1VNC_2 \dots$ sequences, respectively, and are illustrated in Figure 1c and 1d. The velic function for C_1VC_2N sequences begins in the same way as the C_1VC_2 function (Figure 1a), but adds N , whose lowering onset is delayed to avoid (hypernasal) distortion of C_2 . Although lowering does begin before the end of the acoustic period of C_2 , it begins sufficiently late that C_2 is realized before substantial velic port opening occurs. In Figure 1d, the velic function begins in the same way as that for C_1VN in Figure 1b, with the addition of an obstruent whose velic raising onset is delayed to avoid too early a closing of the velopharyngeal port, which would result in distortion in the form of hyponasality.

Finally, the fifth prediction of this model is for $C_1V_1V_2N$ sequences, and is illustrated in Figure 1e. In this case we find a two-stage velic lowering function for a $C_1V_1V_2N$ syllable; the only onset that is delayed (i.e., the only place that

reorganization takes place) is the onset of V_1 —again here, as in all other examples—to insure that there is adequate velopharyngeal closure for C_1 . Lowering for N begins at its natural time (toward the end of V_1 in this representation; because the lowering for N is of much greater extent than that for V_2 , and because the gestures for V_2 and N are added, the velic gesture for V_2 cannot be isolated here, just as the gesture for V could not be isolated in the function for CVN (Figure 1b).

The literature on anticipatory velar lowering is extensive, and for the sake of brevity, not all the published data are discussed here in detail; rather, the focus here is on examples of the different patterns of velic movement and levator palatini EMG potentials that have been reported in a variety of articles. These patterns will be evaluated to determine how well they conform to the predictions of the Bell-Berti and Harris (1981) model. But before turning to the data, a reminder: a number of studies of velic coarticulation that have focused on nasal coarticulation have assumed a neutral specification of velic position for vowels and have not included minimally contrastive utterances, so that there are only limited examples of velic function in oral environments upon which we may draw.²

Beginning with the first prediction of this model (schematized in Figure 1a), there is clear evidence of velic lowering for vowels occurring between obstruent consonants (e.g., Bell-Berti et al., 1979; Bell-Berti, 1980; Bell-Berti & Hirose, 1975; Henderson, 1984; Karnell et al., 1988; Ushijima & Sawashima, 1972), and the published velic functions strongly resemble those of Figure 1a, suggesting that in this prediction, the Bell-Berti and Harris (1981) coproduction theory is supported by the available data. Furthermore, the available levator palatini EMG data clearly show lower EMG potentials for vowels than for their adjacent obstruent consonants (e.g., Bell-Berti, 1973, 1976; Bell-Berti & Hirose, 1975; Fritzell, 1969; Henderson, 1984). Similarly, when we turn to the prediction for CVN sequences (schematized in Figure 1b), predicting that velic lowering begins during the obstruent and continues steadily through the vowel into the nasal consonant, we again find support for the model in the available velic movement data (e.g., Bell-Berti et al., 1979; Bell-Berti & Hirose, 1975; Benguerel et al., 1977a; Henderson, 1984; Kent et al., 1974; Moll & Daniloff, 1971; Ohala, 1971; Ushijima & Hirose, 1974; Ushijima & Sawashima, 1972). What is more, the reported EMG data reveal that there is suppression of levator palatini activity beginning quite early in the vowel-associated portion of the EMG functions in these CVN sequences (Bell-Berti, 1973, 1976; Bell-Berti & Hirose, 1975; Fritzell, 1969; Henderson, 1984).

The model predicts that when a nasal consonant is immediately preceded by an obstruent consonant, as at the end of C_1VC_2N sequences (Figure 1c), velar lowering will be suppressed until the latter part of the obstruent (to prevent distortion); this prediction is also supported by the previously published kinematic data, where velic lowering occurs with greater velocity than it does in sequences in

which N is immediately preceded by V, which is necessary if the velic port is to open in time for nasal coupling to occur for N (e.g., Bell-Berti et al., 1979; Bell-Berti & Hirose, 1975; Moll & Daniloff, 1971). Support for this prediction is evident, too, in levator palatini EMG activity whose suppression for the nasal consonant begins only after completion of the strong obstruent-related peak in EMG potential (e.g., Bell-Berti, 1973, 1976; Bell-Berti & Hirose, 1975). In C_1VNC_2 sequences, the model's fourth prediction (see Figure 1d), that velic lowering will begin as in C_1VN sequences (see Figure 1b) and that velic raising will be suppressed until a sufficiently long period of nasal coupling has occurred for the nasal perception to occur, finds support in a number of kinematic and EMG studies that report sharply rising velic movements and EMG potentials for obstruents immediately following nasal consonants (Bell-Berti, 1973, 1976; Bell-Berti & Hirose, 1975; Benguerel et al., 1977a; Benguerel, Hirose, Sawashima, & Ushijima, 1977b; Fritzell, 1969; Lubker, 1968; Moll & Daniloff, 1971; Ushijima & Hirose, 1974; Ushijima & Sawashima, 1972).

Finally, and perhaps most tellingly for the conflict between feature spread and coproduction models, let us consider the predictions of the Bell-Berti and Harris (1981) model for the CV_1V_2N case. The model predicts that velic lowering will occur in two identifiable stages (one vowel-related and one related to the nasal consonant), so long as the durations of the vowels are sufficiently long that the onset of the velic lowering gesture for the nasal consonant does not begin until after the beginning of the acoustic period of the first vowel (Figure 1e). Although such multistage patterns are described in Benguerel et al. (1977a) as well as in Bell-Berti and Krakow (1991a), it was Bladon and Al-Bamerni (1982) who focused our attention on such patterns. They posited a "hybrid" model of coarticulation that includes both feature spread and coproduction mechanisms. (A second hybrid model has been proposed by Perkell and Chiang, whose 1986 paper focuses on the anticipatory coarticulation of lip rounding.) The hybrid models were developed to account for observations of "two-stage" anticipatory coarticulation effects (velic lowering in some $/V_nN/$ sequences or lip rounding in some $/C_nu/$ sequences; the subscript n indicates a variable number). In the case of anticipatory nasal coarticulation, the authors of these models have claimed that the observation of velic lowering at the beginning of the vowel sequence argues against coproduction models. However, since the hybrid models accept the assumption of "neutral" velic specification for vowels, they cannot distinguish the beginning of velic lowering for the vowel from the beginning of velic lowering for the nasal consonant. On the other hand, the two-stage velic lowering reported by Bell-Berti and Krakow (1991a) and Benguerel et al. (1977a) is precisely that predicted by the Bell-Berti and Harris coproduction model. Figure 2 presents the velic lowering pattern for one token of the sequence $/s\alpha n/$; the vocalic sequence was of sufficient duration that the velic lowering for N did not begin before the acoustic onset of the second segment of the vocalic sequence. As a result, at least the beginning

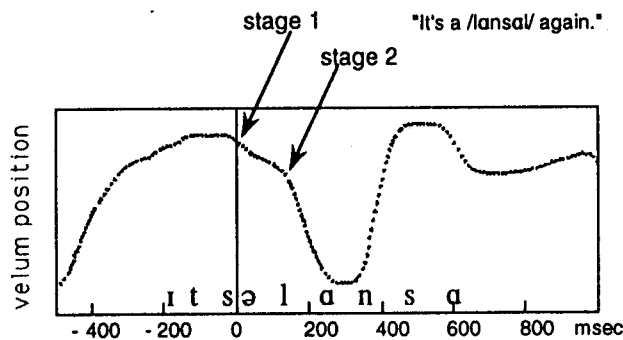


Figure 2. Velic movement trace with multistage lowering pattern.

of downward displacement for the segments in this vocalic sequence does not overlap with (and, thus, is not added to) the onset of downward displacement for the nasal consonant, and we see vowel- and nasal-related lowering. (Similar data are presented in Figure 7 of Benguerel et al., 1977a.)

Additional support for the coproduction models is also found in Bell-Berti and Krakow's (1991a) data for minimally contrastive CV_nN and CV_nC sequences, where the earliest downward displacement in CV_nN sequences has the same time-course as the beginning of downward displacement in CV_nC sequences. Velic position data for such a minimal contrast (*/səlans/* and */sələs/*) are shown in Figure 3a; both position functions begin to move downward near the end of the fricative */s/* and for about 75 msec the functions have essentially the same time-course, after which the nasal sequence function declines steeply and the oral sequence function plateaus. Bell-Berti and Krakow (1991a) have interpreted such data as indicating that both movement traces reflect the vocalic gesture during the period following the */s/*.

Finally, a comment about multiple-stage gestures. Bell-Berti and Krakow (1991a) have reported more-than-two-stage downward displacement patterns in some tokens; examples of such patterns are shown in Figure 3b, in which three separate downward movements are evident in the displacement curve for the oral sequence */seilas/*, presumably one for each segment in the vocalic sequence. In this utterance, the vocalic sequence was of sufficient duration that the velic raising for the sequence-final obstruent did not begin before the onset of the velic gesture for the last segment of the vocalic sequence. As a result, the beginning of the downward displacement for the last segment in this vocalic sequence did not overlap with (and thus was not added to and masked by) the onset of upward displacement for the final */s/*. The early parts of the velic lowering pattern for a token of the nasal sequence */seilan/*, overlaid on that for the */seilas/* sequence, are identical for the early parts of the vocalic sequence, adding support to the claim that the early parts of the functions represent vowel-related velic lowering. In addition, for

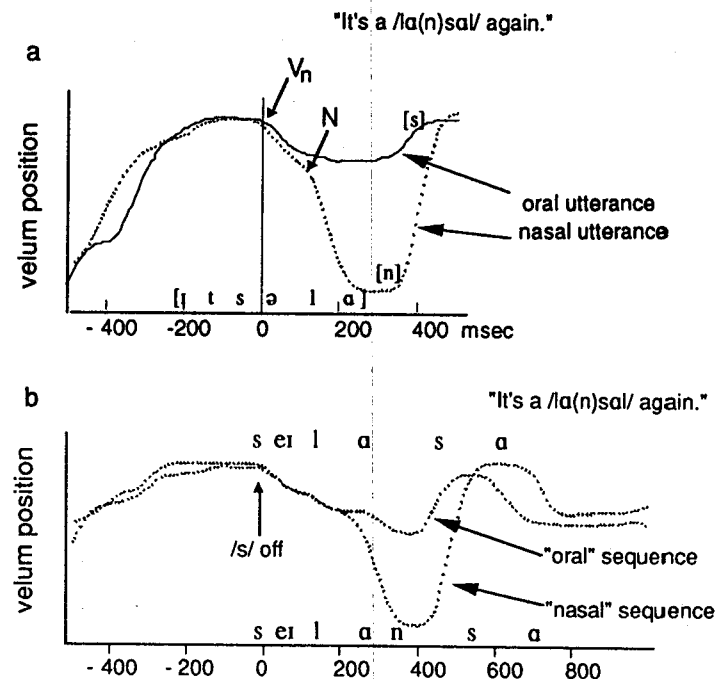


Figure 3. Velic movement traces for minimally contrastive utterances. (a) Nasal utterance is produced with a two-stage lowering gesture; oral utterance is produced with vowel-associated velic lowering corresponding to the first-stage lowering of the nasal utterance. (b) Both are produced with three-stage lowering gestures. Note that the beginnings, corresponding to the earlier oral segments, are identical; differences emerge as the influence of */n/* and */s/* affect the velic gesture for */a/*.

the sequence ending with a nasal consonant, the vowels were of sufficient duration that velic lowering for */n/* did not begin before the onset of the velic gesture for the second segment of the vocalic sequence, and so there are two lowering onsets before lowering begins for the last vowel and nasal consonant (these gestures do overlap, and the gesture for */n/* masks the gesture for */a/*). Both these results are consistent with the predictions of this coproduction theory.

At least two additional phonetic contexts must be mentioned here, even though the predictions of the model for these contexts are not schematized in Figure 1. First, in NV_nN sequences the model predicts velic raising for the vowels, a prediction that finds support in the data of Henderson (1984) and also of Kent et al. (1974).³ Second, in $V_1C_nV_2$ sequences, Bell-Berti (1980) has reported data in which the velum continues to rise during sequences of as many as five obstruents (some lasting as long as 360 msec), beginning to lower only within 50 msec or so of the end of the obstruent string. Her interpretation of those data was that velic position was additive, with the contribution of each successive obstruent in the

string overlapping and hence being added to the raising gesture in progress. Additionally, the fact that peak velic position for the obstruent sequence (occurring about 50 msec before the beginning of the acoustic period for V_2) was strongly influenced by the identity of V_2 provides additional support for this coproduction model that posits greater temporal separation of vowel gestures as the duration of intervening consonant sequences increases.⁴ As a result, consonantal events occurring closer to V_1 than V_2 will be more strongly influenced by V_1 , and those occurring closer in time to V_2 will be more strongly influenced by V_2 .

4. CONCLUSION

This analysis of the results of a number of studies of velic function and coarticulation suggests three conclusions. First, the basic unit of speech organization is segmental. Second, gestures for segment sequences are realized sequentially, with overlapping of gesture onsets and offsets. Third, carryover coarticulation is more pervasive and important in determining the time course of articulatory movements than is anticipatory coarticulation.

But even accepting that this view is an accurate representation of the primary units of speech organization, it is clear that other factors are also at work in determining the velic kinematic patterns observed in speech. Recently, several studies have revealed that segmental velic position is influenced by syllable stress. Thus, nasal consonants have been shown to be associated with lower velic positions, and oral segments with higher velic positions, when they occur in stressed, rather than in unstressed, syllables (e.g., Krakow, 1986, 1987, this volume; Vaissiere, 1988). In addition, the location of a segment within a syllable has been shown to influence the extent of velic movements for nasal consonants, with greater movements and lower minimum velic positions for nasal consonants occurring in syllable-final than in syllable-initial position (Krakow, 1989), whereas differences in the extent of velic movements between syllable-initial and syllable-final oral consonants remain to be determined. Finally, velic position is also influenced by the location of a segment within a syntactic unit: McClean (1973) has shown that the location of marked junctural boundaries affects velic behavior, and Bell-Berti and Krakow (1991b) and Krakow, Bell-Berti, and Wang (1991) have reported a declination in peak velar position for oral segments from the beginning to the end of sentences.

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NOTES

¹It has been hypothesized (Matisoff, 1975; Ohala, 1975) that oral obstruents having glottal or pharyngeal constrictions may be produced with velic positions that are lower than those for their oral-cavity-constriction counterparts.

²It is important to bear in mind that it may be difficult to interpret data from different studies because of different underlying assumptions about the nature of coarticulation and the specification of articulatory patterns. Furthermore, these assumptions may not have been made explicit and may have influenced experimental results in ways that were not controlled for in the experimental design (Boyce, Krakow, & Bell-Berti, 1991; Boyce, Krakow, Bell-Berti, & Gelfer, 1990; Gelfer, Bell-Berti, & Harris, 1989).

³See, particularly, the velic displacement functions in the Kent et al. (1974) Figure 8, for the sentence *Many a man knew my meaning*.

⁴When V_2 is a high vowel, peak velic position for the obstruent sequence is significantly higher than when V_2 is a low vowel.

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