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Investigation of the Timing of Velar Movements during Speech

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High-speed cinefluorographic films were taken of four normal subjects speaking English sentences containing various combinations of nasal consonants (N), consonants (C), and vowels (V) at normal speaking levels and rates of production. Word and syllable boundaries were designed to fall across the sequences in various ways. From frame-by-frame tracings, measures of velar movement and velopharyngeal opening were made. Results indicate extensive anticipatory coarticulation of velar movement toward velopharyngeal opening in CVN and CVVN sequences such that velar movement toward opening began during the approach to the initial vowel in all cases and some velopharyngeal opening was observed on all vowels. For NC and NCN sequences, velar movement toward closure for the consonant usually began during the preceding nasal such that some velar closure was observed during all plosive and fricative consonants used. These results directly contradict the hypothesis that a CV-type syllable is the minimal unit of coarticulation and production. The data are consistent with the predictions of a model which assumes a phone-sized input unit and which incorporates a "look ahead" mechanism whereby an articulatory feature can be systematically anticipated prior to the occurrence of the phone with which that feature is associated.

INTRODUCTION

In recent years there has been considerable study of the coarticulation of speech sounds. Numerous investigators[1–7] have proposed models of articulation of varying completeness which account for the phenomenon of coarticulation. Certain of the models postulate a syllable or larger-sized unit as the basic input unit of articulation production,[1,5] while others contend that phone-sized units are more likely.[2–4,7,8] The issue is unresolved, but there is speculation that there may be input units of several sizes to the articulatory system depending on the level of production and the articulators involved.[6,9]

Kozhevnikov and Chistovich[1] defined the CV construction (where C represents any number of consonants) as an "articulatory" syllable and concluded that such a syllable represents the basic unit of articulation. This conclusion was based on two considerations: (1) A CV syllable is the smallest unit of speech to show relative invariance of duration with changes in rate of production, and (2) the degree of anticipatory coarticulation of lip protrusion, labial and lingual movements, and voicing is maximum within such syllables and minimum between them. On the other hand, Henke's[4] model of production assumes a phone-sized input wherein each phone consists of a set of articulatory targets or features for each of the articulators involved. The model includes a forward scanning mechanism which permits articulators to commence articulations in advance of the phone for which they are appropriate as long as these articulations do not conflict with the articulation of phones preceding the anticipated one. Such a look-ahead device predicts the anticipatory coarticulation of lip protrusion over four consonants preceding a vowel observed by Daniloff and Moll[8] for speakers of English. Even so, the Henke model seems inadequate for predicting the precise timing relationships among syllables, words, and phrases that have been observed.[1,10]

Additional studies of articulation are needed to test for the maximum extent of coarticulation, the full range of coarticulations possible for each independent articulator, and careful quantification of the amounts and timing of coarticulation in different phonetic environments.

The present study was designed to observe velar coarticulation, since little is known about the nature, timing, and extent of its coarticulatory behavior.[11–15] We proposed to test the timing and extent of coarticulatory velar movements toward velar closure or opening by preparing consonant, vowel, and nasal sequences which were inserted in meaningful sentences.

I. PROCEDURES

Since speech is usually produced in sentence-sized utterances, diverse phonetic sequences were constructed to fit within meaningful sentences so that the sequences would be spoken in a "normal" manner. The sentences were spoken at conversational rate and effort level while high-speed cinefluorographic films were taken. From these films, a number of measurements of velar movement were made.

A. Subjects

Four young adult males, aged 26–32 years, served as subjects. The four had no history of orofacial pathology, appeared to have normal orofacial structures when examined by an experienced speech pathologist, and were judged by several trained phoneticians to have no obvious defects of articulation, intonation or voice quality. Three subjects were characterized as having dialects of American English typical of the Midwestern states, while the fourth had a dialect of Canadian English typical of Montreal, Canada.

B. Speech Samples

Various words and word sequences were selected to provide different phone strings involving vowels (V), nasal consonants (N), and non-nasal consonants (C). Anticipatory coarticulation was studied in the CN, CVN, and CVVN sequences listed in Table I. Carryover of velopharyngeal opening was examined in the NC and NVC sequences listed. Also studied were NCN, NVN, and NV# sequences, where # represents utterance break at the end of a sentence. The samples in Table I involve a variety of vowels, as well as plosive, fricative, lateral, voiced, and voiceless consonants. Two students with training in phonetics provided a phonemic transcription of the subjects' utterances taken from tape recordings of the experimental sentences. No major deviations from the intended phonemic sequences were observed.

TABLE I. A listing of the phonetic sequences used in this study and sentences in which the sequences were produced.

EXPERIMENTAL SEQUENCES:

Opening movements	Closing movements	Complete nasal context
CN	NC	NCN
CCN	NCC	NCCN
CVN	NCCC	NVN
CVVN	NVC	NV#

EXPERIMENTAL SENTENCES: (Sequences studied are underlined.)

(1) Have Terry enforce one of the rules.
(2) He wants to reinforce the conflict.
(3) No one shows interest in a dumb smile.
(4) Connie came to Free Ontario for the firm's money.
(5) Never fill warm tanks with freon gas.
(6) Entice my friends not to come.
(7) A few inane acts never appeal.

C. Equipment and Procedures

Cinefluorographic films were made using the techniques outlined by Moll.[16] Subjects were seated in a dental chair with their heads between a 150 KV x-ray tube and a 9-in. image intensifier. Head position was held constant by use of a head positioner incorporating ear rods and a forehead clamp. The image intensifier output was filmed with a Mitchell 16-mm high-speed camera. Films for this study were taken at 150 frames/sec. Simultaneous voice recordings were made utilizing an Electrovoice model 644 microphone and Magnecord model 728 tape recorder.

Each subject practiced reading the sentences at conversational rate and effort level with "normal" inflection. After being seated and aligned to the x-ray-intensifier ensemble, barium sulfate paste (Rugar) was smeared on the midline of the dorsal tongue surface, lips, and midline of the hard palate. Prior to phonating the sentences, subjects were filmed while clenching between their teeth a plastic rod containing embedded steel spheres of known size to provide a basis for adjusting projected films to life size for tracing.

D. Measurements and Data Analysis

The general procedures for analysis consisted of projecting the films to life size using a modified Kodak Analyst projector and making frame-by-frame tracings (of the type shown in Fig. 1) for each of the underlined sequences in Table I.

To facilitate measurement of velar movement (VM), a transparent tracing template was made for each subject as shown in Fig. 1, which included the upper

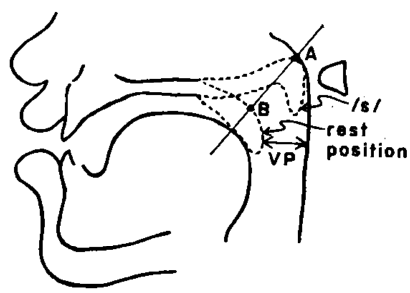

FIG. 1. A line drawing showing the structures traced on each cinefluorographic frame. Also shown are the velum positions for /s/ and for "rest" used to derive line AB. Velar movement along this line away from point B was defined as velar movement (VM). Velopharyngeal opening (VP) is shown as the minimum distance between the velum and the posterior pharyngeal wall.

incisors, hard palate, and tubercle of the Atlas. Since these structures have relatively fixed positions, each tracing could be superimposed upon the template for easy measurements of VM along a preestablished line.

Two measures of velum activity were made: velar opening (VP) or minimum velar–pharyngeal wall distance, and velar movement (VM), which reflected the position of the velum along a line coincident with the line of velar movement for each subject. The line for velar movement (see Fig. 1) was established by locating the highest point (A) of the superior surface of the velum during closure for /s/, the phoneme on which greatest velar elevation was noted for all subjects. Then, with the velum at nonphonatory rest, the point B on the posterior–superior surface of the velum nearest to point A was located and velar movement was then defined as the motion along line AB in millimeters from point B. We feel that this is a realistic, but only grossly approximate measure of velar movement, since velar movement is somewhat curvilinear.

Repeated tracings and measurements on 85 frames yielded standard errors of measurement of 0.91 mm for VM and 0.45 mm for VP. Identification of the timing of other articulatory movements was accomplished using the procedures of Daniloff and Moll.[8] This was done by observing the movements of major articulators (other than the velum) and locating the time points at which primary articulators for a given phone began movement toward or away from a contact-closure or steady position. Repeated determinations of 85 of these time points revealed an average error of 1.38 frames (8.1 msec) in locating these points.

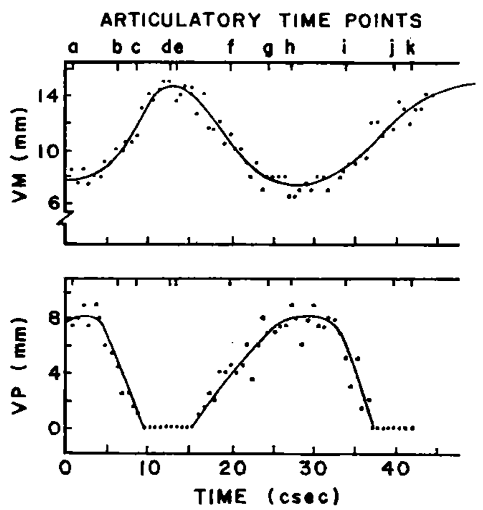

Fig. 2. A sample data plot showing the variations of (VM) and (VP) with time during the sequence /mtæŋks/ in "warm tanks." The horizontal axis at the bottom of each graph shows time in csec and the horizontal axis at the top of each graph indicates the time points at which various articulatory events occurred. These time points are identified as follows: (a) lip closure, (b) tongue toward /t/, (c) contact for /t/, (d) lips open, (e) /t/ contact opens, (f) /æ/ target achieved, (g) tongue toward /ŋ/, (h) contact for /ŋ/, (i) tongue toward /s/, (j) /s/ slit opens, and (k) /k/ contact opens.

The two velar measures were plotted as a function of time as shown in Fig. 2. Velar movement (VM) is shown in the upper part of this figure and velopharyngeal distance (VP) below. The time points for other articulatory movements are designated on the horizontal line between the two graphs. The smooth curves were fitted to the data by eye; however, the curve fitting was not extremely difficult, owing to the small scatter in the data points. From these plots, the time points at which velar movement began, or at which velopharyngeal distance started to change, were identified in relation to the timing of other articulatory movements. For example, in Fig. 2, which presents data for the /mtæŋks/ sequence in "warm tanks," the decrease in the VM measure was judged to begin at the time point at which the lips open after closure for /m/ and at which the tongue–alveolar ridge contact opens for /t/. In other words, this movement toward opening in anticipation of /ŋ/ starts about at the point that the tongue begins to move toward the vowel /æ/. Note that the beginning of velar opening (VP) is slightly delayed from VM. Increase in the VM measure for the /ks/ sounds was judged to begin shortly after the tongue–palate contact for /ŋ/ is achieved and shortly before the tongue starts to move toward a position appropriate for /s/. Although there might be some disagreement concerning the judgments of the beginning points of movement, even relatively rigid criteria for detecting movement would not significantly affect the basic data to be presented.

II. RESULTS

Primary data analysis was made using VM. The speaker controls velopharyngeal port opening by muscle contractions which give rise to velar movements. Since these movements often occur in advance of any change in velopharyngeal port size, it was judged that VM would provide a better indication of the timing of neural commands to the velum than VP.

It was first noted that the presence or absence of word boundaries within the sequences did not affect the timing of velar movements. This observation confirms the results of Daniloff and Moll,[8] who observed like behavior for lip protrusion. At low levels of juncture between words, when no clausal break or major syntactical boundary falls at the juncture between words, articulation proceeds smoothly across the two words as predicted by MacNeilage[2] and Henke.[4] Thus, data for different junctural conditions were combined.

Figure 3 summarizes the data for VM for CN, CCN, and NCN sequences. The bar graph indicates the number of sequences (of a total of 23) exhibiting initiation of velar movement in relation to the beginning of articulatory approach to the non-nasal consonant (Ca), the first point of articulator closure or steady state (Cc), the beginning of articulatory approach to the nasal consonant (Na), and the achievement of articulatory contact for the nasal (Nc). Velar movement for a sample was considered to begin at the time of a given articulatory event (e.g., at Cc) only if it began within ±2 cinefluorographic frames (13.34 msec) of that articulatory event. In addition, the time between each of these points was divided into halves so that an even finer distribution of velar movement starting points, over time, could be achieved. It should be noted that whenever there was uncertainty in establishing the starting point of VM, a later rather than earlier time point (cine frame) was chosen, so that these data are conservative estimates of the extent of velum coarticulation of opening, showing a smaller extent of coarticulation than might have been observed.

It can be noted from Fig. 3 that, in a CN or CCN sequence, velar movement toward opening is initiated just before or during the primary articulator approach to the nasal (17 of 23 sequences, or 74% of the cases). The greatest single number of movements toward opening (57%) occurred just before or coincided with the start of articulator movement toward the nasal. It is as if either consonantal closure for the consonant preceding the nasal or the start of articulator movement toward the nasal "triggers" or releases signals to the velum which cause velar movement, as predicted by Henke,[4] and contrary to the predictions of Kozhevnikov and Chistovich.[1] It might be speculated that velar movement is synchronized to closure contact for the preceding (C) or, even more likely, to the onset of articulator movement toward the nasal (N) through low level kinesthetic–proprioceptive feedback loops.[4]

Figure 4 presents data for VM during velar closure in all NC-type sequences. In 52 of 53 cases (98%) velar movement toward closure began just before or coincident with the start of articulator movement toward the consonant. It was also observed that velopharyngeal closure (VP=0) was always achieved at least 15 msec before the articulatory release of a consonant preceded by a nasal, even when another nasal followed the consonant. Thus, velopharyngeal closure was always

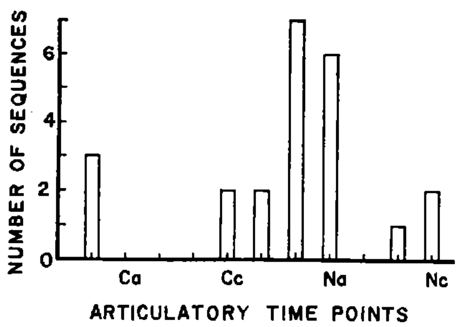

FIG. 3. Frequency of occurrence of the beginning of velar opening movements for CN, CCN, and NCN sequences ($n=23$) relative to the following timepoints: Ca, Na—time points at which articulators began their approach toward articulatory closure or steady state for C or N, respectively; Cc, Nc—time points at which articulatory closure or steady state was achieved for C or N. The time intervals between Ca, Cc, Na, and Nc were segmented into halves, and all beginnings of velar movement occurring within any half are located at the points marked on the horizontal axis between the labeled points.

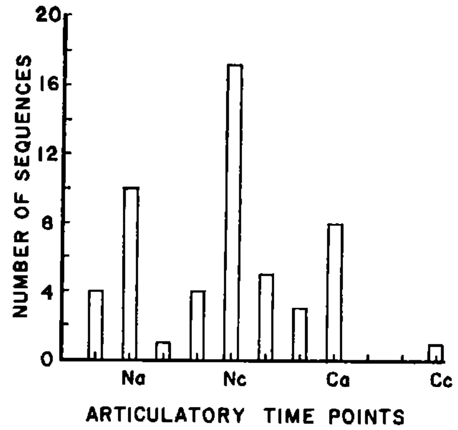

FIG. 4. Frequency of occurrence of the beginning of velar closure movements for NC, NCC, NCCC, and NCN sequences ($n=53$) relative to the following time points: Ca, Na—time points at which articulators began their approach toward articulatory closure or steady state for C or N, respectively; Cc, Nc—time points at which articulatory closure or steady state was achieved for C or N. The time intervals between Na, Nc, Ca, and Cc were segmented into halves, and all beginnings of velar movement occurring within any half are located at the points marked on the horizontal axis between the labeled points.

observed for some period of time during consonantal articulation, a finding inconsistent with those of Bjork,[15] who observed lack of closure for some consonants in nasal contexts. In fact, in 83% of the 53 NC sequences, movement toward velar closure began *during* the nasal consonant, at a time point when one would expect the velopharyngeal port to be maximally open. Since the largest single number of movements toward closure began at the moment of nasal consonant contact, it is tempting to speculate that this articulatory contact triggers the velar closure movement for the following non-nasal consonant; however, VM starting points are scattered along the entire time period between the beginning of the approach to the nasal consonant and the release of the nasal consonant articulation. At best, it can be concluded that movement toward velar closure is initiated long before the articulatory contact for the non-nasal consonant, usually during the preceding nasal.

Figure 5 displays data for NVC sequences. In 90% of the sequences, velar movement toward closure began during the nasal consonant, during the approach to the vowel, or during the steady-state portion of the vowel. In 74% of these sequences, movement toward closure began during the period of articulatory closure for the nasal consonant. In three sequences, no velar closure gesture was observed. In each of these cases, the consonant following the vowel was /w/ or /l/ followed by a nasal consonant or an end of utterance. Quite commonly, velar closure was incomplete during the vowel, although there was a steady movement toward closure throughout the vowel. Thus, NC and NVC sequences are quite similar in terms of velar closure, except that in the NVC sequences movement toward closure begins a little later than in NC sequences and

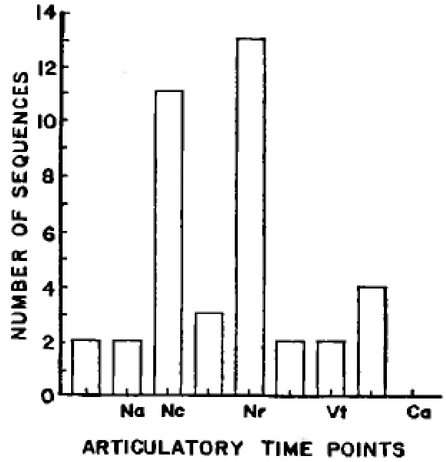

FIG. 5. Frequency of occurrence of the beginning of velar closure movements for NVC sequences ($n=39$) relative to the following time points: Na, Ca—time points at which articulators began movement toward articulatory closure or steady state for C or N, respectively; Nc, Nr—moments at which articulatory closure for the nasal was first made or released, respectively; Vt—the time at which the vowel articulatory target was first achieved. Velar movements which began between time points Nc, Nr, Vt, Ca are grouped at the points marked on the horizontal axis between the labeled points.

closure may not be complete during the vowel, whereas it is during the consonant in NC sequences.

Figure 6 summarizes data on the beginning of velar-opening movements in CVVN sequences. In every instance, the opening gesture started at or before the beginning of tongue movement toward the first vowel in the sequence. The majority of the velar movements started shortly after articulatory contact for the initial consonant. Thus, velar opening, presumably associated with the nasal consonant, coarticulates over as many as two vowels preceding the nasal, even though a word boundary may occur within the sequence. There was always some velopharyngeal port opening present for

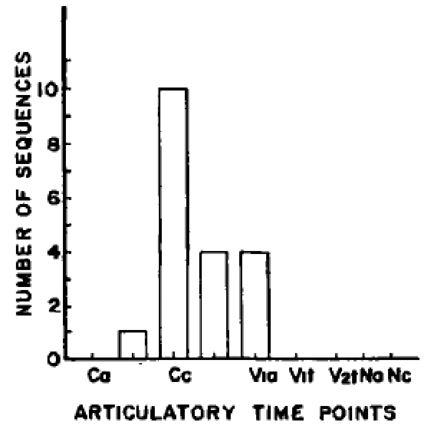

FIG. 6. Frequency of occurrence of the beginning of velar opening movement for CV_1V_2N sequences ($n=19$) relative to the following time points: Ca, V_1a, Na—time points at which articulators began their approach toward articulatory closure or steady state for C, V_1, or N, respectively; Cc, Nc—time points at which articulatory closure was first achieved; Vt—the time at which the vowel articulatory target was first achieved. Velar movements which began between time points Ca, Cc, V_1a are grouped at the points marked on the horizontal axis between the labeled points.

both vowels and, quite often, there was as much opening during the vowels as during the nasal consonant.

The results for the CVN sequences in Figs. 7(a) and 7(b) are similar to those for CVVN sequences. However, some variation occurs, depending on the identity of the consonant sound. Of the 32 samples in which the consonant was a stop or fricative, all but three showed velar opening movement beginning no later than the start of tongue movement toward the vowel. In 72% of these 32 cases, movement toward opening started during the closure phase of the initial consonant. Of 12 samples in which the consonant was /w/, however, the opening gesture occurred much earlier; it was always initiated before the articulatory release of the consonant. In fact, two of the samples exhibited no velopharyngeal closure during the /w/.

One experimental sample, the word "money," provided a nasal–vowel sequence followed by an utterance termination. For this sequence, one subject exhibited intermittent velopharyngeal closure for the final vowel /i/, one showed movement toward closure though closure was not achieved, and two subjects exhibited no velar closure movement, the velum remaining fully open throughout the vowel.

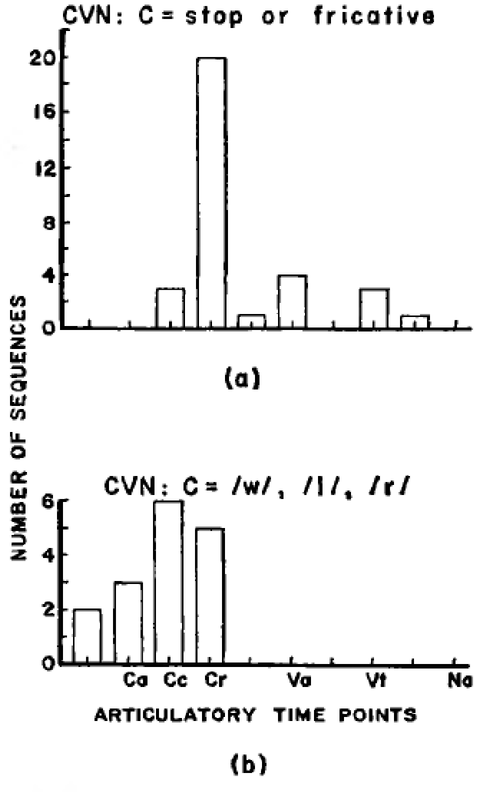

FIG. 7. (a, b) Frequency of occurrence of the beginning of velar opening movement for CVN sequences ($n=32$, C=stop or fricative; $n=16$, C=/w/, /l/, /r/) relative to the following time points: Ca, Va, Na—time points at which articulators first began movement toward articulatory closure or vowel steady state for C, V, or N, respectively; Cc, Cr—time points at which articulatory closure for C was first achieved or released, respectively; Vt—the time point at which the vowel articulatory target was first achieved. Velar movements which began between time points Cr, Va, Vt, Na are grouped at the points marked on the horizontal axis between the labeled points.

III. DISCUSSION

Undoubtedly the major finding of this study is that, in sequences in which a nasal consonant is preceded by one or two vowel sounds, the velar-opening gesture for the nasal is initiated near the beginning of primary articulatory movement toward the first vowel in the sequence. Further, the presence of a word boundary within the sequence does not affect the relative timing of the velar gesture. This finding cannot be explained readily by the Kozhevnikov–Chistovich[1] model, which assumes that the basic unit of articulation is an "articulatory CV-type syllable" consisting of any number of consonants followed by a vowel. They hypothesize that articulatory commands for the entire syllable are specified simultaneously with the start of the syllable insofar as the commands are noncompeting with earlier sounds. These investigators concluded that coarticulation should thus be maximal within such a syllable and minimal between syllables. When applied to velar movement on a CVVN sequence, such as in "freon" or in "free Ontario," their model predicts that velar opening associated with /n/ would begin no earlier than the primary articulator approach to /n/, that is, at the beginning of the articulatory syllable. The present data show clearly that the velar-opening gesture is initiated at the beginning of the articulatory approach to the first vowel in the sequence. A similar discrepancy exists between the data for CVN sequences and predictions from the Kozhevnikov–Chistovich model.

It appears that the present data can be explained by the articulatory model proposed by Henke.[4] The input to the model is assumed to be a string of phone-sized segments, each of which is specified in terms of a set of articulatory goals. The goals (targets) or features associated with an input segment constitute a finite set and are varied discretely in time. They are invariant environment-independent shapes and positions of articulators. The articulators move toward these specified goals; however, they may not be attained. The articulatory positions actually attained depend on past positions of the articulators and on the timing of sequential inputs. Henke also suggests a high-level "look-ahead" or scanning of future input units, which allows a coarticulatory anticipation of certain features of such units when this does not conflict with the specified goals of more immediate units. Table II depicts an application of Henke's model to velar movements. It is assumed that the specified velar goals (or features) are as follows: for a non-nasal consonant, the velum should be closed; for a nasal consonant or an utterance ending, it should be open; for English vowel sounds, it is hypothesized that velar position is unspecified (no articulatory goal for velopharyngeal closure or opening is specified for vowels at the input). It should be noted that, although a binary specification system is assumed, such an assumption is not critical to this discussion.

Examples of predictions from the model are given in the lower part of Table II. The model predicts that when an unspecified value of the velar feature is encountered, the system scans to the next specified value of that feature and begins immediately to assume it. Thus, for a CVVN sequence, it would be predicted that velar opening for the nasal consonant would be initiated at the beginning of the first vowel in the sequence, a prediction in agreement with the data obtained in this study. For NVC sequences, the model predicts that velar closure movement for the consonant will begin after the nasal consonant is produced. Again, this prediction is in agreement with the findings. The velar opening observed on a vowel preceding an utterance ending also is predicted by this model. In fact, the only major discrepancies between the observed data and the predictions relate to the consonants /w/ and /l/. It will be recalled that in CVN sequences involving these consonants, velar opening often began during the consonant. Since these sounds are considered by some to be phonetically somewhat vocalic in nature,[11] it might be hypothesized that the velar goal for such sounds is "unspecified" or, alternatively, that they have a specified goal which is intermediate between a velar-closed and a velar-open specification.

The present observations on the timing of velar movements are consistent with a model which assumes phone-sized input units, a "look-ahead" mechanism and an unspecified velopharyngeal closure feature for English vowels. A profitable next step would be the study of velar-movement characteristics in a language such as French, which has a phonemic contrast between nasalized and non-nasalized vowels. To achieve such a contrast, the velar specifications likely would be different than those assumed here for English.

Regardless of the validity of the articulatory model described above, the data of this study are clearly not consistent with models,[1,5] which assume that CV-type syllables are the basic units in which speech is pro-

TABLE II. Application of Henke's[a] model of speech articulation to velar movement.

ASSUMED VELAR SPECIFICATIONS:

Speech segment	Velar specification	Symbol
Non-nasal consonant (C)	closed	+
Nasal consonant (N)	open	−
Vowel (V)	unspecified	0
End of utterance (#)	open	−

EXAMPLES OF MODEL PREDICTIONS:

(1) Speech sounds: C -- V -- V -- N
Velar specifications: + 0 0 −
Predicted beginning of velar opening (at first V)

(2) Speech sounds: N -- V -- C
Velar specifications: − 0 +
Predicted beginning of velar closure (at V)

[a] See Ref. 4.

grammed. Models assuming units larger than syllables may, of course, be consistent with these observations; however, unless one wishes to contend that velar movement is somehow different than other articulatory characteristics, it appears that these results cast serious doubt on the use of a CV-type syllable model to explain data on coarticulation. Instead, these data and other studies of articulation[8,18–21] support the notion that models[3,4] utilizing phone-sized input units are appropriate for description of articulation. These models usually presume that each input unit consists of a unique set of articulatory features which are produced by articulators operating in parallel fashion.

The perceptual significance of coarticulatory effects have been demonstrated in part by Liberman *et al.*[22] It is interesting to speculate that anticipatory, relatively long, and slow onsets of a given articulatory feature such as nasality may temporally smear the cues for a given phone segment. Listeners may detect this anticipatory smearing of such a feature as nasality and utilize this information to predict and identify phone segments. Recent work by Ali *et al.*[23] confirms this speculation. Listeners were reliably able to detect the presence of coarticulated nasality in CVN and CVVN sequences when the final nasal, including the VN transition, was removed.

ACKNOWLEDGMENTS

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