Superior lateral pharyngeal wall movements in speech

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Medial movements of the lateral pharyngeal wall at the level of the velopharyngeal port were examined by using a computerized ultrasound system. Subjects produced CVNVC sequences involving all combinations of the vowels /a/ and /u/ and the nasal consonants /n/ and /m/. The effects of both vowels on the CVN and NVC gestures (opening and closing of the velopharyngeal port, respectively) were assessed in terms of movement amplitude, duration, and movement onset time. The amplitude of both opening and closing gestures of the lateral pharyngeal wall was less in the context of the vowel /u/ than the vowel /a/. In addition, the onset of the opening gesture towards the nasal consonant was related to the identity of both the initial and the final vowels. The characteristics of the functional coupling of the velum and lateral pharyngeal wall in speech are discussed.

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INTRODUCTION

In normal speech, the velopharyngeal port acts to partition the oral and nasal cavities and thus enables the production of distinct nasal and oral sounds. The valving action of the velopharyngeal mechanism consists of elevation and retraction of the velum along with medial gestures of the posterior and lateral pharyngeal walls (Dickson and Dickson, 1972; Skolnick, 1969). The present study was designed to examine the spatio–temporal characteristics of lateral pharyngeal wall movements at the level of the velopharyngeal port with special attention to the effects of phonetic context on these gestures. It was aimed at assessing the contribution of lateral pharyngeal wall movements to the overall organization of the velopharyngeal mechanism.

To date, the velopharyngeal mechanism in speech has been studied primarily in terms of velar movements and the activity of its muscles. It has been shown that the velum is elevated for obstruents and phonemically oral vowels (Bell-Berti, 1976; Bell-Berti and Hirose, 1975; Lubker, 1968), and is lowered for nasal consonants (Bell-Berti, 1976; Bell-Berti *et al.*, 1979; Benguerel *et al.*, 1977a,b; Lubker *et al.*, 1970). In addition, it has been observed that velar elevation is different for different vowels, and is often related to vowel height or openness; that is, the velum has a higher position for high vowels such as /i/ and /u/, and a lower position for /a/ (Bell-Berti, 1976; Bell-Berti *et al.*, 1981; Kunzel, 1979; Moll, 1962; Lubker, 1968; Seaver and Kuehn, 1980).

Studies of the velopharyngeal mechanism also have been concerned with pharyngeal wall movements. Overall, it has been observed that the lateral walls show considerable medial movement for non-nasal consonants and vowels, and very little medial movement for nasal consonants (Shprintzen *et al.*, 1975; Shprintzen *et al.*, 1977; Skolnick *et al.*, 1975; Ryan and Hawkins, 1976; Zagzebski, 1975). In addition, it has been shown that lateral pharyngeal wall displacements differ for high and low vowels with high vowels having greater medial movement than low vowels (Niimi *et al.*, 1978).

Although some spatio–temporal similarities between pharyngeal wall and velar movements have been demonstrated, the study of phonetic context has been restricted primarily to velar movements. The coarticulation of nasal and non-nasal sounds has been demonstrated primarily in terms of velar lowering for nasal consonants and its elevation for oral consonants and vowels, or in terms of the velopharyngeal port opening and closing. It has been shown that velar lowering for a nasal consonant starts well before the oral articulatory movement for this consonant (Benguerel, 1974), and near the beginning of the oral articulatory movement for a preceding oral vowel (Bladon and Al-Bamerni, 1982a,b; Kent *et al.*, 1974; McClean, 1973; Moll and Daniloff, 1971; Ushijima and Hirose, 1974). In addition, it has been shown that vowel identity affects the extent of velar elevation or its position for preceding or following obstruents and nasals; in other words, the higher the vowel, the higher the velar position during the preceding or following obstruents or nasals (Bell-Berti *et al.*, 1979).

Information on coarticulation in the movements of the lateral pharyngeal wall can also shed light on the characteristics of the velopharyngeal mechanism. Our aim was to identify characteristics of lateral pharyngeal wall movement which are similar to those of velar movement; covariation of movement kinematics was assumed to be a property which defines the functional organization of the velopharyngeal synergy.

In this study, movements of the lateral pharyngeal wall were monitored during the production of consonant–vowel–nasal–vowel–consonant (CVNVC) sequences. The movement amplitude, duration, and point of onset of movement relative to specific acoustic events in the CVN (velopharyngeal opening) and NVC (velopharyngeal closing) gestures were examined. In addition, the effects of the vowels preceding or following a nasal consonant upon the pharyngeal gestures towards the nasal consonant and away from it were assessed.

It should be emphasized that only the movements of the pharyngeal wall were examined. Inferences about the nature of the velopharyngeal mechanism were derived by comparing empirical data gathered here with findings from the literature on velar movement. Ideally, it would be desirable to measure movements of both the velum and the pharyngeal wall simultaneously with a single measurement instrument in order to obtain direct evidence on the magnitude and the temporal relationships which characterize the synergy. Evidence of this kind could be obtained using x-ray techniques although the invasive nature of the x-ray procedure makes it undesirable. The ultrasound technique which was used here to measure the movements of the lateral pharyngeal wall cannot be adapted to monitor the movements of the velum. However, the inability to obtain direct evidence on velopharyngeal coupling is offset by its noninvasive nature, by its high temporal and spatial resolution, and by the relatively large volume of data which can be collected, thus permitting the use of true factorial statistical designs.

I. METHOD

A. Speech sample and subjects

The stimuli consisted of eight different CVNVC types. The initial and final consonants were always /p/. The nasal consonants were /n/ and /m/, and the vowels were the low and high back vowels /a/ and /u/, respectively. Each sequence was preceded and followed by the sound /ə/ (e.g., /əpamapə/). The vowels were equally stressed and the utterances were produced at a normal speech rate. The vowels /a/ and /u/ were chosen for their kinematic characteristics rather than their phonological properties; the vowels are know to entail pharyngeal wall excursions of differing extent.

Three male adults with normal speech served as subjects. Subjects RK and TO were native English speakers, with Canadian and New Zealand dialects, respectively. Subject AP was a native Hebrew speaker and fluent in Canadian English.

B. Apparatus and procedure

Lateral pharyngeal wall movements were monitored by using a computerized pulsed ultrasound system (see Keller and Ostry, 1983; Ostry *et al.*, 1983; Ostry and Munhall, 1985; Parush *et al.*, 1983, for details).

The ultrasound signals were generated and received by a Picker model 104 ultrasonoscope with a 3.5-MHz single element transducer. An acoustic record was obtained simultaneously. The ultrasound and acoustic data were both recorded at a 1-kHz rate.

The individual recording trials lasted 3.5 s each. In each trial, the subject repeated a given CVNVC utterance continuously. Typically, two or three repetitions per trial were produced. The order of the various CVNVC types was randomized across trials.

In order to monitor lateral pharyngeal wall movements at the level of the velopharyngeal port, the ultrasound transducer was placed against the external neck wall, beneath the earlobe, and behind the ramus of the mandible. This placement was used previously by Ryan and Hawkins (1976) and Zagzebski (1975). The transducer was held against the subject's external neck wall by an adjustable holding rig.

The orientation of the transducer was determined by having the subject slowly rotate her/his head against the transducer. Initial placement was based on the detection of ultrasound reflections from the pharyngeal wall during nonspeech gestures such as swallowing; swallowing results in a strong medial gesture of the pharynx. Once the lateral pharyngeal wall was located, the final position for recording was determined such that the movement amplitude between the nasal and obstruent consonants in repetitions of the word /sæŋkə/ was maximized. This criterion was employed since previous reports have indicated that the maximum changes in the velopharyngeal port area occur between obstruents and nasal consonants (e.g., Bell-Berti, 1980).

Figure 1 shows the position of the lateral pharyngeal wall, in the upper panel, and the corresponding acoustic signal during repetitions of /sæŋkə/. The upper peaks of the position record indicate a more medial position of the pharyngeal wall. It can be seen that there is a large amplitude excursion of the pharyngeal wall in moving from the position for the nasal consonant /ŋ/ to the position for the oral syllable /kə/. Thus the ascending direction in the position record can be viewed as corresponding to the closing gesture of the velopharyngeal port (for oral sounds), whereas the descending direction corresponds to the opening of the port (for nasal sounds).

It should be noted that, when measured in this fashion, pharyngeal wall position corresponds to different points along the axis of the ultrasound beam. Points along this medial axis rather than spatial coordinates of particular tissue points are thus reported (see Keller and Ostry, 1983; Ostry *et al.*, 1983, for details). Accordingly, the terms *position* and *velocity* refer to positions and rates of change along the measurement axis, not to individual tissue points. Since the numerical magnitude of the movement amplitudes, durations, and velocities obtained with this technique are comparable to those obtained when individual tissue points are imaged, it appears that ultrasound measurement along the principal axis of movement can provide a useful quantification of the movement kinematics.

Ten trials were recorded in each of the eight treatment conditions (four vowel pairings $\times$ two consonants). The raw data were analyzed by dividing the duration of the trial into equal intervals and fitting natural cubic spline functions to the set of values, termed knots, formed by the interval averages at their midpoints (the algorithm used here is found in Johnson and Riess, 1977). Cubic splines are a set of piecewise polynomial functions which pass through each of the knots and have first and second derivatives that are continuous at the knots. Splines were selected for this application because they are numerically differentiable and make no *a priori* assumptions about the overall form of the function. In the present study, a 45-ms interval width for averaging was selected; this results in a movement bandwidth of about 23 Hz and an average absolute difference between the raw data and the spline of 0.03 cm/measurement (Keller and Ostry, 1983; Munhall and Ostry, 1985). (The standard error due to system resolution was approximately 0.010 cm in this study.)

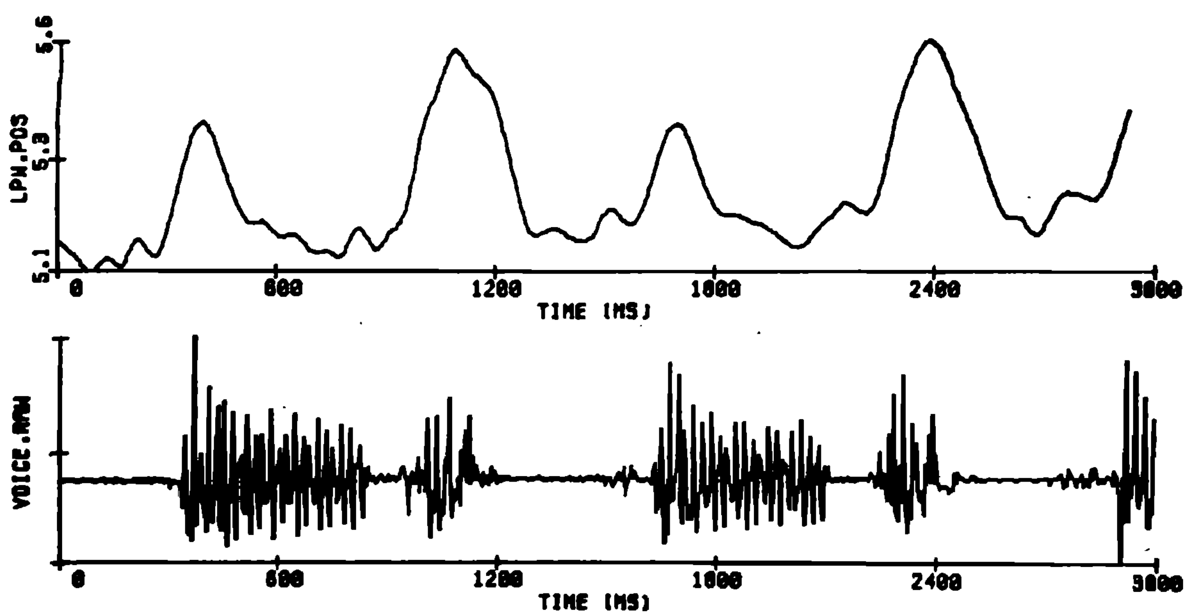

FIG. 1. Medial movements of the lateral pharyngeal wall and the corresponding speech waveform during repetitions of the word /sæŋkə/. (The units on the ordinate of the upper record correspond to the distance between the ultrasound transducer and the lateral pharyngeal wall.) The medial position is at the top of the upper panel; the lateral position is at the bottom.

C. Measurements

For analysis purposes, the CVNVC sequence was divided into the lateral pharyngeal wall gesture towards the nasal consonant (the CVN gesture) and pharyngeal gesture away from the nasal consonant (the NVC gesture). The vowel in the CVN gesture is referred to as the initial vowel, and the vowel in the NVC gesture as the final vowel. The movement amplitude, duration, and the point of movement onset relative to specific acoustic events were computed for each gesture. The six variables, three for each gesture, are displayed in Fig. 2.

The position of the articulator is plotted in the top panel of Fig. 2 in terms of the distance from the transducer to the pharyngeal wall, with more medial positions shown at the top of the record. The distances were obtained by converting the time from the ultrasound emission to the reception of the echo from the pharyngeal wall to a distance measure (the conversion assumed an average speed of ultrasound in soft tissue of 1540 m/s; see Goss *et al.*, 1978, for details). $D\,1$, the amplitude of the CVN gesture, was computed as the distance between the zero-velocity position of the pharyngeal wall during the initial consonant and the zero-velocity position for the nasal consonant (point of maximum velopharyngeal opening). $T\,1$, the duration of the CVN gesture, was computed as the time between the same two zero-velocity points. The time interval between the zero-velocity point during the initial oral consonant (maximum displacement) and the voice onset of the initial vowel, shown as A in Fig. 2, was taken as an index of the timing of the CVN movement onset. Longer intervals indicate an earlier onset of the movement towards the vowel and nasal consonant, and thus may reflect more nasalization of the initial vowel.

The movement amplitude, duration, and timing of the NVC movement onset were computed in a similar fashion, and are also shown in Fig. 2. $D\,2$, the amplitude of the NVC gesture, was computed as the distance between the zero-velocity position for the nasal consonant (maximum opening point) and the zero-velocity position for the final consonant. The duration of the NVC gesture $T\,2$ was computed as the time between these two zero-velocity points. The time between the first zero-velocity point and the voice offset of the final vowel, shown as interval B in Fig. 2, was taken as an index of the timing of the NVC gesture onset. Longer intervals indicate earlier onsets of the gesture away from the nasal consonant, and thus may reflect less nasalization of the fol-

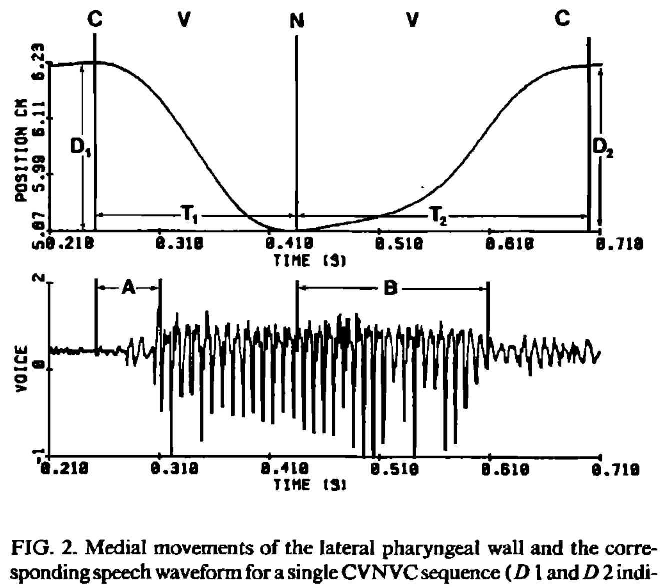

FIG. 2. Medial movements of the lateral pharyngeal wall and the corresponding speech waveform for a single CVNVC sequence ($D\,1$ and $D\,2$ indicate movement amplitude; $T\,1$ and $T\,2$ indicate duration; A and B indicate the point of onset of movements relative to acoustic events).

lowing oral vowel. Voice offset for interval B was identified in the raw acoustical signal as the point of termination of periodicity.

In scoring the data, tokens were rejected if either the initiation or the termination of voicing was not clearly distinguishable in the acoustic record or if mulitiple peaks in the ultrasound position record made it difficult to identify either the point of initiation or termination of a gesture. The data rejection rate was similar across conditions. The results reported here are based on ten to fifteen tokens per subject in each of the eight treatment conditions.

Note that the measurements reported here give the amplitude of *movement* of the pharyngeal wall rather than the pharyngeal wall *position*. The reporting of movement rather than position is wholly a consequence of the ultrasound technique and need not be taken to suggest that articulator excursions rather than vocal tract configurations are the controlled variables in the production of speech. It is worth noting, however, that these alternatives may, in fact, be indistinguishable. In current work on human limb movements, the question has been posed whether movements are planned in task-space or joint-angle coordinates. Interestingly, with appropriate theoretical assumptions, both positions can be shown formally to be tenable (e.g., Hollerbach *et al.*, 1985).

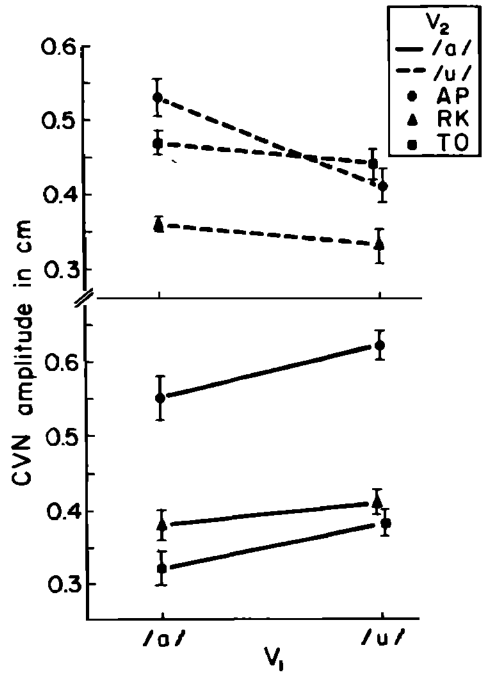

FIG. 3. Mean amplitude of the pharyngeal CVN gesture plotted against the two initial vowels, for each of the two final vowels. (The means and standard errors are pooled across the two consonants.)

II. RESULTS

Lateral pharyngeal wall movements were examined in two ways. One analysis considered the kinematic characteristics of the CVN and NVC gestures as a function of the vowel in a given sequence. The second analysis dealt with the effects of a final vowel on the preceding CVN gesture (anticipatory effect) and the effects of an initial vowel on the following NVC gesture (carryover effect).

Separate three-way analyses of variance (two initial vowels $\times$ two final vowels $\times$ two nasal consonants) were carried out for each of the three subjects. The analyses did not reveal any consistent main effects or interactions related to the nasal consonants. As a result, the data were pooled over both consonants for the presentation of the figures and the tables.

A. Kinematic characteristics

1. The CVN gesture

Previous studies have demonstrated that the identity of the vowel (i.e., open or closed) affects velar position for preceding or following nasal consonants (Bell-Berti, 1976; Lubker, 1968; Kunzel, 1979). In the present study, the effects of vowel identity on pharyngeal wall movements were assessed by examining the kinematics of the CVN gesture.

The amplitude of the CVN gesture is plotted in Fig. 3 against the initial vowel, for each of the final vowels. The solid lines indicate that the final vowel was /a/; the dashed lines indicate /u/. It can be seen that the amplitude of the CVN gesture depends on the identity of both the initial and the final vowel. When the final vowel was /a/ (bottom panel), the amplitude of the CVN gesture was less with the initial vowel /a/than with /u/. In contrast, when the final vowel was /u/(top panel), the amplitude of the CVN gesture was less with the initial vowel /u/ than with /a/. For subjects AP and TO, the interaction between the initial and final vowels was reliable [$F(1,95) = 14.37$, $p<0.001$; $F(1,92) = 5.20$, $p = 0.02$, respectively]. The pattern for subject RK was similar. However, the interaction was not statistically reliable ($p>0.05$).

There was a significant effect of the initial vowel on the duration of the CVN gesture [$F(1,95) = 22.14$, $p<0.001$; $F(1,92) = 22.88$, $p<0.001$; $F(1,96) = 6.66$, $p<0.01$, for AP, TO, and RK, respectively]. The average duration of the CVN gesture, along with standard errors, is presented in Table I, for all subjects. It can be seen that the duration of the CVN gesture was longer with the initial vowel /u/.

Previous studies have shown that velar lowering onset for the nasal consonant in CVN sequences starts near the beginning of the lingual movement for the vowel (Kent *et al.*, 1974; McClean, 1973; Bladon and Al-Bamerni, 1982a,b; Moll and Daniloff, 1971). The movement onset of the CVN gesture was examined here relative to the voice onset of the vowel, as a function of the vowel in the sequence. For subjects TO and RK, there was a significant effect of the initial vowel upon the timing of the movement onset of the CVN gesture [$F(1,92) = 86.92$, $p<0.001$; $F(1,96) = 5.24$, $p = 0.02$, respectively]. When the initial vowel was /u/, the CVN gesture started earlier than when the vowel was /a/. For subject AP, the timing of the movement onset of the CVN gesture was not affected by the identity of the initial vowel ($p>0.05$). These effects are displayed in Fig. 4.

The onset of the CVN gesture relative to the voice onset of the initial vowel is shown as a function of the initial vowel for each of the final vowels. Overall, the CVN gesture started

TABLE I. Means and standard errors of the duration (in seconds) for the VCN and NVC gestures, for each of the four utterance types.

	Subject		
Sequence	RK	TO	AP
		CVN gesture	
/aNa/	0.189	0.161	0.252
	0.006	0.013	0.008
/uNa/	0.195	0.207	0.296
	0.007	0.010	0.007
/aNu/	0.150	0.179	0.189
	0.005	0.006	0.006
/uNu/	0.181	0.222	0.213
	0.010	0.010	0.006
		NVC gesture	
/aNa/	0.256	0.213	0.225
	0.007	0.009	0.011
/aNu/	0.232	0.194	0.258
	0.005	0.011	0.006
/uNa/	0.251	0.246	0.192
	0.006	0.007	0.008
/uNu/	0.225	0.212	0.224
	0.008	0.007	0.007

before the voice onset of the vowel, with the exception of the sequence /paNup/ for subject TO. The gestures started as early as 82 ms before voicing for TO, 70 ms for RK, and 78 ms for AP. The occurrence in two subjects (TO and RK) of an earlier movement onset of the CVN gesture with /u/ may indicate greater nasal coarticulation of high vowels preceding nasal consonants. Consistent with this result are reports by Bladon and Al-Bamerni (1982a,b) who have shown that the velopharyngeal opening time is related to the vowel preceding the nasal consonant.

2. The NVC gesture

It has been demonstrated previously that vowel identity affects the velar gesture from a nasal consonant towards an obstruent. The amplitude of the NVC gesture was examined here as a function of the vowel in the gesture. For all subjects, there was a significant effect of the final vowel upon the amplitude of the NVC gesture [$F(1,92) = 50.44, p < 0.001$; $F(1,96) = 3.97$, $p < 0.05$; $F(1,95) = 17.54$, $p < 0.001$, for TO, RK, and AP, respectively]. However, for subjects AP and TO, this effect should be interpreted with reference to a significant interaction between the initial and final vowels [$F(1,95) = 20.50, p < 0.001$; $F(1,92) = 11.50, p < 0.001$].

In Fig. 5, the amplitude of the NVC gesture is plotted against the final vowel, for each of the initial vowels. The solid lines are for the initial vowel /a/, and the dashed lines are for the initial vowel /u/. For all subjects, it can be seen that the amplitude of the NVC gesture is affected strongly by the phonetic context only when the initial vowel is /u/ (top panel); in this context, the amplitude of the NVC gesture was less when the final vowel was /u/ rather than /a/. This differential effect, which was dependent on the initial vowel, was reflected in the proportion of variance accounted for. When the initial vowel was /a/, the proportion of variance in the NVC movement amplitude accounted for by the final vowel was not significant ($p > 0.01$, for AP and RK, $r^2 = 0.09, p = 0.03$ for TO). However, when the initial vowel was /u/, the r^2 was 0.41, 0.16, and 0.60 for AP, RK, and TO, respectively ($p < 0.001$ for all subjects). The small amplitude of the pharyngeal NVC gesture with the final /u/ is

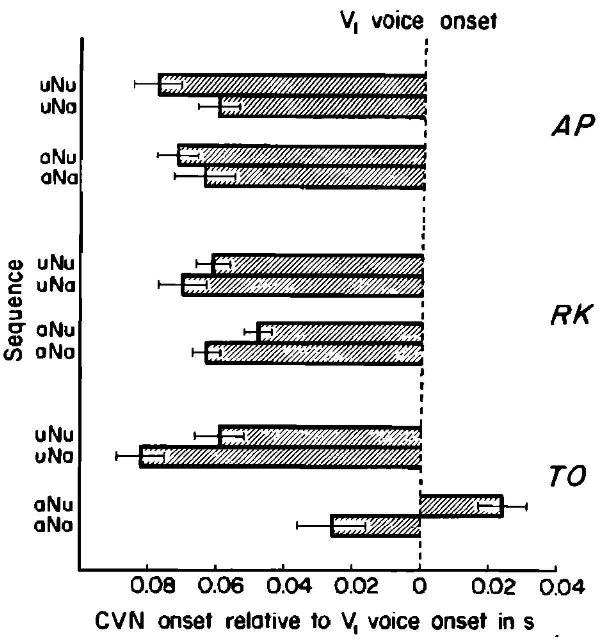

FIG. 4. The mean interval between the movement onset of the CVN gesture and the voice onset of the initial vowel in the sequence, shown for each of the four CVNVC types. (Voice onset of the initial vowel is indicated by the vertical dashed line; the upper-case N indicates that the data are pooled across both nasal consonants.)

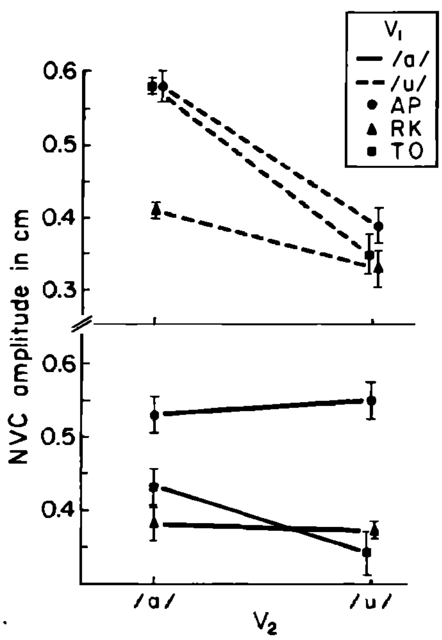

FIG. 5. The mean amplitude of the pharyngeal NVC gesture plotted against the two final vowels, for each of the two initial vowels. (Means and standard errors are pooled across the two consonants.)

similar to the pattern observed for velar displacements during NVC sequences (Bell-Berti *et al.*, 1981).

There was a significant effect of the final vowel on the duration of the NVC gesture. The mean duration of the NVC gesture, along with standard errors, is presented in Table I. It can be seen that subjects TO and RK have similar patterns; that is, the duration of the NVC gesture is shorter when the final vowel is /u/ [$F(1,92) = 11.67$, $p < 0.001$; $F(1,96) = 11.77$, $p < 0.001$, for TO and RK]. In contrast, for subject AP, the duration of the NVC gesture is longer when the final vowel is /u/ [$F(1,95) = 31.44$, $p < 0.001$].

Earlier studies have shown that the velar NVC gesture begins during the nasal consonant (Kent *et al.*, 1974; Moll and Daniloff, 1971). The analysis conducted here indicated significant effects of the final vowel on the timing of movement onset of the pharyngeal NVC gesture relative to the final consonant closure [$F(1,95) = 68.51$, $p < 0.001$; $F(1,92) = 174.71$, $p < 0.001$; $F(1,96) = 3.83$, $p = 0.05$, for AP, TO, and RK, respectively]. For RK and TO, the interval was shorter when the final vowel was /u/, whereas, for AP, the interval was longer when the final vowel was /u/. Overall, the gesture started as early as 262 ms before the offset of the final vowel for subject TO, 208 ms for subject AP, and 175 ms for subject RK. This onset time relative to the voice offset may suggest that the movement started earlier in the acoustic period of the vowel or even sometime during the nasal consonant, a possibility which is in agreement with previous velar movement studies.

3. Summary

It was demonstrated that the kinematic characteristics of lateral pharyngeal wall CVN and NVC gestures were related to the vocalic content of these sequences. When the final vowel was /u/, the CVN gesture had less amplitude, longer duration, and, for two subjects, an earlier movement onset with the initial vowel /u/ than with /a/. Similarly, the NVC gesture had less amplitude and, for two subjects, shorter duration with the final vowel /u/ than with /a/.

B. Coarticulation

1. Anticipatory effects

The effects of future segments on a given gesture were examined in terms of the effects of the final vowel on the amplitude of the preceding CVN movement. Significant effects of the final vowel were obtained for all subjects. For subjects AP and RK, the amplitude of the CVN gesture was less when the final vowel was /u/ [$F(1,95) = 24.50$, $p < 0.001$; $F(1,96) = 5.53$, $p = 0.02$]. For subject TO, the amplitude of the CVN gesture depended on an interaction between the initial and final vowels [$F(1,92) = 5.20$, $p = 0.02$]. For subjects AP and RK, there was a stronger effect of the final vowel on the amplitude of the CVN gesture when the initial vowel was /u/ ($r^2 = 0.47$, $p < 0.001$, for AP and 0.13, $p < 0.05$, for RK). When the initial vowel was /a/, the proportion of variance accounted for by the final vowel was not significant for either subject ($p > 0.05$).

There was also an effect of the final vowel on the duration of the CVN gesture. For both AP and RK, the duration of the CVN gesture is shorter when the final vowel is /u/, regardless of the identity of the initial vowel [$F(1,95) = 106.43$, $p < 0.001$; $F(1,96) = 15.88$, $p < 0.001$, respectively]. For TO, the CVN duration was unaffected by differences in the initial vowel ($p > 0.05$).

There was an effect of the final vowel on the timing of the movement onset of the CVN gesture relative to the voice onset of the initial vowel. In Fig. 4, it can be seen that the CVN gesture started earlier for RK and TO as indicated by longer intervals, when the final vowel was /a/ [$F(1,92) = 20.59$, $p < 0.001$; $F(1,96) = 8.00$, $p < 0.005$]. For AP, the CVN gesture started earlier when the final vowel was /u/ [$F(1,95) = 7.49$, $p < 0.01$]. In other words, the quality of the post-nasal vowel had an effect on the extent of nasalization of the initial oral vowel, with two of the subjects showing greater coarticulation of nasality when the final vowel was /a/.

2. Carryover effects

The effects of preceding segments on a given gesture were examined in terms of the effect of the initial vowel on the amplitude of the NVC gesture. For AP and TO, the amplitude of the NVC gesture depended on both the initial and final vowels [$F(1,95) = 4.75$, $p < 0.05$; $F(1,92) = 14.33$, $p < 0.001$]. For RK, the amplitude of the NVC gesture was unaffected by the initial vowel ($p > 0.05$).

3. Summary

The anticipatory effects of a vowel following a nasal consonant on the amplitude of the pharyngeal wall opening movement for that consonant were more evident when the initial vowel was /u/: The amplitude of the gesture was less when the final vowel was /u/ than when it was /a/. In addition, for two subjects the gesture had a shorter duration and started later when the final vowel was /u/. Carryover effects of the initial vowel on the following pharyngeal closing gesture away from the nasal consonant were also present. However, the pattern depended on the identity of the final vowel.

III. DISCUSSION

The pharyngeal coarticulation demonstrated in this study can be described in terms of the effects of the vowels on the movement towards the nasal consonant and away from it. The movement from the oral CV towards the nasal consonant started before the voice onset of the vowel for all subjects. The duration of the interval between the movement onset and the vowel voice onset was related to the identity of the vowels preceding and following the nasal consonant. This trend is similar to that reported for the CVN velar gesture in previous studies and is considered an indication of coarticulation of nasality (Bladon and Al-Bamerni, 1982a,b; Kent *et al.*, 1974; McClean, 1973; Moll and Daniloff, 1971).

The gesture from the nasal consonant towards the following oral VC started well ahead of the closure for the final consonant. The possibility that the NVC gesture started sometime during or even at the beginning of the acoustic period of the vowel suggests that the vowel following a nasal consonant is less nasalized than vowels preceding a nasal consonant. This trend is in agreement with previous acoustic analysis (Ohala, 1971) and velar movement patterns (Bell-Berti *et al.*, 1981) which have shown that there is greater nasality of vowels preceding than following nasal consonants.

In the spatial domain, the effects of a vowel following a nasal consonant on the amplitude of pharyngeal movements were similar for both movement towards and away from the consonant: When the vowel was /u/, the amplitudes of both movements were less than when the vowel was /a/. This trend was particularly strong when the vowel preceding the nasal was /u/. Similar patterns also have been observed for velar movements associated with nasal consonants (Bell-Berti *et al.*, 1979; Bell-Berti *et al.*, 1981; Moll, 1962; Ushijima and Sawashima, 1972). In these studies, velar position for a nasal consonant was found to be higher in the context of high vowels and lower with low vowels.

The similarity of the pharyngeal wall movements measured here to the patterns of velar movement described in the literature is consistent with the view that these two structures operate as a functional synergy in the action of the velopharyngeal port. On the basis of this similarity, we infer that the synergy acts through a coupling of the amplitudes, durations, and movement onset times of the lateral pharyngeal wall and velar movements. We use the term coupling to imply covariation. We assume that a kinematic linkage exists between the articulators for these variables. However, we do not assume that they covary strictly in a ratiomorphic way.

Note that covariation in the amplitudes, durations, and movement onset points of velar and pharyngeal wall movements does not rule out compensatory adjustments between these structures to preserve the form of the acoustical output in spite of individual differences between talkers or trial-to-trial variation in the movements of either of the articulators. This so-called "motor equivalence" was not observed directly in this study but may have played a role in some of the individual differences that were observed.

On the assumption that the amplitudes and durations of velar and pharyngeal wall phenomena covary, a model proposed by Bell-Berti (1980) to account for velar function also seems to account for some of the pharyngeal dynamics observed here. The model postulates the specification of both temporal and spatial parameters of the movement. Specifically, the amplitude of the velopharyngeal opening or closing is specified as an interaction between the spatial goals for the nasal consonant and the various vowels. Thus the model would predict that the velopharyngeal port would be more open for nasal consonants in the context of a low vowel than a high vowel.

Similar principles can account for the pharyngeal movement patterns observed here. The spatio–temporal properties of the pharyngeal movement are determined by a combination of two factors. The first is the effect of the nasal consonant on the pharyngeal position for the adjacent vowel. That is, the vowel /a/ is produced at a more open position in the context of nasal consonants than in the context of obstruents (e.g., Ushijima and Sawashima, 1972). The second factor is the effect of the vowel on the pharyngeal position for the adjacent nasal consonant. That is, a nasal consonant will be produced in a more open position in the context of /a/ as opposed to /u/ (e.g., Bell-Berti *et al.*, 1979). An interaction of these two factors characterizes the varying amplitudes of pharyngeal movements found in this study. For example, when the initial and final vowels were /a/, the amplitude of both opening and closing gestures was less than when the initial vowel was /u/ and the final vowel was /a/. In the /aNa/ sequence, both vowels were produced in a more open position, and, consequently, the amplitudes of the opening and closing gestures were small. However, in the sequence /uNa/, the vowel /u/ was produced in a more closed position while the nasal consonant was produced in a more open position because of the vowel /a/. This caused the amplitude of the opening and closing gestures to be greater.

The effects of the vowels on the temporal characteristics of the pharyngeal opening and closing gestures indicate the possible overlapping production of both the vowels and the nasal consonant. Particularly, the duration and timing of movement onset were related to the vowel following the nasal consonant. When the final vowel was /a/, the CVN gesture, for two subjects, was of longer duration and started earlier than with /u/. In other words, the initial vowel was presumably more nasalized when the final vowel was /a/. Thus the production of the initial vowel and the extent of its nasality (i.e., the extent of its coarticulation with the nasal consonant) seem to be linked to the final vowel. The overall characteristics of the opening and closing gestures may result therefore from the co-production of the vowels and the nasal consonant. Such a model was proposed by Fowler (1980), and was also suggested as a possible explanation of the effects of the vowel on velar function (Bell-Berti *et al.*, 1979).

Several individual differences have been observed in this study. Although only three subjects were tested, it is clear that these differences reflect variations in subject's movement patterns rather than measurement error since the standard errors of estimate are small for both movement amplitudes and durations. The lack of complete uniformity across subjects in this data does not make these findings less physiologically important. Indeed, they point to a general property of the coordinated nature of speech, namely, that constraints are defined across the oral cavity in such a way that the appropriate acoustical form is preserved in spite of variations in the individual movement trajectories.

This suggestion is consistent with the several reports of individual differences in the operation of the velopharyngeal mechanism (see Bell-Berti, 1980, for a review). The prevalence of these differences has led some investigators to suggest that there are several individual strategies in the control of the velopharyngeal port. For example, Bladon and Al-Bamerni (1982b) have shown two different temporal patterns of velar lowering for a nasal consonant relative to the voice onset of the preceding vowel. Bladon and Al-Bamerni concluded that speakers may therefore have two alternative production strategies. It is possible that the differences observed here across the three subjects may reflect differences in the control techniques of the velopharyngeal mechanism.

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