Lower pharyngeal wall coarticulation in VCV syllables

A. Parush
Tel Aviv University, Tel Aviv, Israel

D. J. Ostry
McGill University, Montreal, Quebec H3A 1B1, Canada

(Received 30 October 1991; accepted for publication 8 April 1993)

Speech movements of the lower pharyngeal wall were recorded in two subjects using pulsed-echo ultrasound. The focus of the study was the pattern of coarticulation of pharyngeal wall movements. Using nonsense utterances as test material, both anticipatory and carryover coarticulatory effects were observed. The identity of the final vowel in VCV sequences affected the kinematic characteristics of the initial VC transition. Both the amplitude and the duration of the movement between the initial vowel and the consonant were greater when the final vowel was /u/ rather than /ɑ/. Similarly, the initial vowel affected the kinematic characteristics of the final CV transition. The amplitude of the movement from the consonant to the final vowel was greater with the initial vowel /u/ as opposed to /ɑ/. The coarticulatory patterns observed in this study are similar to those previously reported for the tongue dorsum and upper pharynx [Parush *et al.*, J. Acoust. Soc. Am. **74**, 1115–1125 (1983); Parush and Ostry, J. Acoust. Soc. Am. **80**, 749–756 (1986)].

PACS numbers: 43.70.Bk, 43.70.Aj

INTRODUCTION

Several studies have suggested that the lower pharynx in the vicinity of the epiglottis may play a role in the production of constriction for back vowels (Perkell, 1969; Perkell and Nelson, 1982; Stevens, 1972; Wood, 1979). In the present study we have examined the coarticulatory patterns of the lower pharynx using pulsed-echo ultrasound. The work complements our earlier ultrasound studies of coarticulatory patterns of the tongue dorsum (Parush *et al.*, 1983) and upper pharynx (Parush and Ostry, 1986). The aim was to assess similarities in the patterns of coarticulation in the three articulators. The strategy in each study has been to manipulate the identity of the initial or final vowel in a VCV sequence and examine the spatial and temporal effects on movements toward the other vowel. This procedure provides measures of anticipatory and carryover coarticulation for the three articulators which can be compared directly.

There is a general narrowing of the lower pharynx for low back vowels such as /ɑ/ that is achieved by lowering and retraction of the tongue dorsum, and by contraction of the pharyngeal walls (Lindquist and Sundberg, 1971; Perkell, 1969; Wood, 1979). Several ultrasonic observations have indicated that there is inward movement of the lateral pharyngeal walls (the side walls of the pharynx) during the production of low back vowels (Kelsey *et al.*, 1969a; Kelsey *et al.*, 1969b; Minifie *et al.*, 1970; Zagzebski, 1975). Conversely, little inward or medial movement of the pharyngeal walls has been observed during the production of high vowels such as /u/ or /i/. These patterns have also been observed in lateral view x-ray studies (Kent and Moll, 1969; Perkell, 1969; Perkell and Nelson, 1982; Wood, 1979).

Evidence for the participation of the pharyngeal walls in the production of vowels is found in the patterns of muscular activity of the pharynx. Electromyographic (EMG) activity is greater for low back vowels than for high vowels in the superior and middle constrictors (Bell-Berti, 1971; Minifie *et al.*, 1974). Greater EMG activity has also been observed in the glossopharyngeal muscle for the vowel /ɑ/ (Smith, 1971). In addition, EMG amplitudes are greater for low back vowels than for high vowels such as /u/ in the activity of the palatopharyngeus (Bell-Berti, 1971; Fritzel, 1969). Overall, the activity patterns of pharyngeal muscles suggest that the pharyngeal walls have a role in articulatory constriction for low back vowels.

Recordings of pharyngeal movements and the activity of pharyngeal muscles indicate that the pharynx functions as an articulator during vowel production. Coarticulation has also been reported in pharyngeal wall movement. Kelsey *et al.* (1969b) have shown that lateral pharyngeal wall movements during the production of the vowel /ɑ/ vary as a function of the phonetic context in VCV sequences. Perkell (1969) has shown that the pharynx begins to narrow, during the oral closure for the consonant /t/, anticipating the final vowel in /hətV/ sequences. Thus coarticulation has been demonstrated in pharyngeal wall movements, but there is little detailed information about its characteristics as phonetic context varies.

I. METHODS

Lateral pharyngeal wall movements at the level of the angle of the mandible were examined during the production of VCV sequences that were composed of back vowels and velar and labial intervocalic stop-consonants. The amplitude and duration of the pharyngeal movement from the initial vowel to the consonant (the VC gesture) were examined as a function of the final vowel (anticipatory coarticulation). Similarly, the movement from the consonant to the final vowel (the CV gesture) was examined as a function of the initial vowel (carryover coarticulation). Pharyngeal movement onsets times were also examined relative to specific acoustic events. Thus, the general strategy was to seek evidence of coarticulation by manipulating one of the vowels in the VCV sequence and examining the effect on a number of kinematic and acoustical parameters of the other vowel which reflect coarticulation. These particular utterances and measurements were chosen because they result in the largest amplitude movements of this articulator and enable direct comparison with our earlier ultrasound studies of tongue dorsum and velar coarticulation (Parush *et al.*, 1983; Parush and Ostry, 1986).

II. SPEECH SAMPLE AND SUBJECTS

The speech sample consisted of 8 different VCV types. This inventory was made up of the back vowels /ɑ/ and /u/ and the stop-consonants /k/ and /p/. Each VCV was preceded by the sound /əp/ and followed by /pə/ (e.g., /əpɑkɑpə/). Subjects were instructed to stress both vowels equally. (The stress task was performed according to instruction.) Ten tokens of each utterance type were recorded.

The experiment was divided into several blocks, with transducer placement unchanged within a block. Speech trials of approximately 3.5 s each were recorded. In each trial, subjects repeated a given VCV sequence two or three times. The order of the various VCV types was randomized within each block and was also randomized across subjects. Two male adults with normal speech served as subjects. Both subjects, PK and BW, were native Canadian English speakers.

III. APPARATUS AND PROCEDURE

Lower pharyngeal wall movements were recorded using a single element pulsed ultrasound system (see Keller and Ostry, 1983; Ostry *et al.*, 1983; Ostry and Munhall, 1985; Parush *et al.*, 1983; Parush and Ostry, 1986, for details). Ultrasound signals were generated by a Picker model 104 ultrasonoscope with a 3.5-MHz transducer. The ultrasound and sound pressure signals were digitized simultaneously at a 1-kHz rate. The low sampling rate for speech was sufficient for the identification of the points of acoustical signal onset and offset that were of interest in this study.

The ultrasound transducer was placed against the external neck side-wall, about 1 cm posterior to the angle of the mandible. This placement location was used previously by Minifie *et al.* (1970). Zagzebski (1975) compared the recordings obtained in this location to recordings obtained from higher placement locations along the external neck wall. He concluded that transducer placement posterior to the angle of the mandible corresponds to the level of the constriction location for low back vowels. The placement of the transducer relative to the subject's head is shown in Fig. 1. This position was used to record medial-lateral movements of the pharyngeal side-wall.

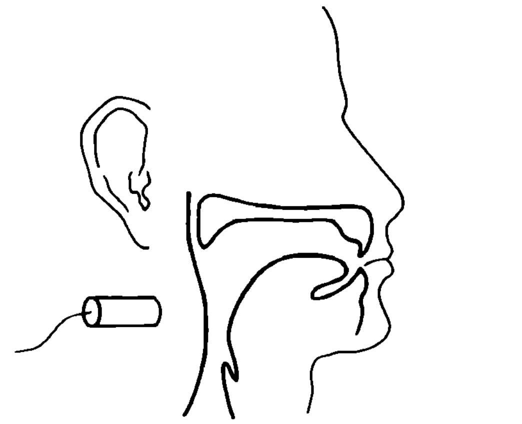

FIG. 1. The ultrasound transducer against the external neck wall for the recording of the lower lateral pharyngeal wall movements.

The transducer was held in a fixed position and orientation against the subject's neck by an adjustable positioning apparatus that was fixed relative to the ground. The subject's head was not fixed and could be rotated about the transducer to obtain a suitable testing position. Initially, the ultrasound echoes from the lateral pharyngeal wall were detected through nonspeech gestures such as swallowing. The final position and orientation for recording were obtained by maximizing the measured distance between the pharyngeal wall positions for the vowels /ɑ/ and /u/. This was achieved by having the subject slowly rotate his head against the transducer while repeating /ɑ/ and /u/ or /kɑ/ and /ku/. Repetitions of this maneuver were recorded several times to verify that a maximum pharyngeal position difference was observed between the vowels /ɑ/ and /u/. An example of lateral pharyngeal wall movement during the positioning maneuver is displayed in Fig. 2. In the recording position, the head was not noticeably turned. However, some error may have been introduced by head orientations which were not orthogonal to the long axis of the ultrasound transducer, that is, by orientations in which the head was slightly turned rather than straight forward. Head orientation was not monitored in this study.

The distance from the transducer to the lateral pharyngeal wall for repetitions of /kɑ-ku/ is plotted in the upper panel of Fig. 2. The corresponding speech waveform is shown in the bottom panel. The higher peaks in the pharyngeal record indicate more medial positions of the pharyngeal wall. It can be seen that there was greater inward movement during the production of the low back vowel /ɑ/ than the high vowel /u/. The more medial position for /ɑ/ corresponds to a narrowing of the pharynx for low vowels and can be contrasted with a wider pharynx for high vowels.

It should be noted that this technique measures the distance along the axis of the ultrasound beam from the transducer head to the lateral pharyngeal wall. It does not measure the changing position of specific points on the pharyngeal wall. As a consequence, error may be present in the measured distances if different tissue points lie along the axis of the ultrasound beam over the course of a trial. However, to the extent that the transducer position is or-

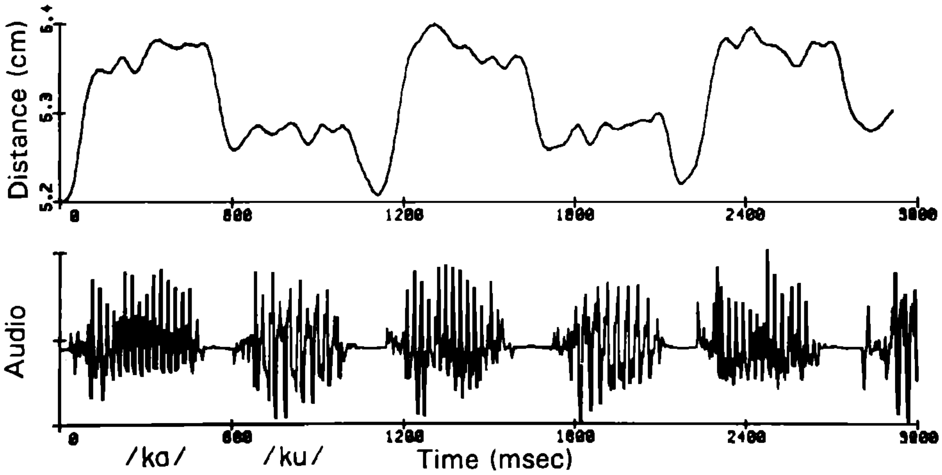

FIG. 2. Lateral pharyngeal wall movements and the corresponding acoustic waveform during repetitions of the syllables /ka-ku/. (The units on the ordinate correspond to the distance in cm between the ultrasound transducer and the lateral pharyngeal wall.)

thogonal to the external neck wall and that movements of individual points are primarily in a single plane, the measured distances will be correlated with changes in the spatial coordinates of tissue points.

The signals were smoothed with natural cubic spline functions (Johnson and Riess, 1977). In this experiment, each recording trial was divided into 80 equal intervals of 43.2 ms and the average value of the measurements in each interval was used as a knot for the spline interpolation program. In order to determine the spacing of knots, average absolute differences between the spline and the raw data were calculated for a range of interval widths. It was found that when knots were calculated on the basis of interval widths of less than 45 ms, there was little effect on the average absolute difference between the raw data and the spline. The choice of 43.2 ms (80 kn) as the averaging interval for calculation of the spline resulted in an average absolute difference between the raw data and the spline function of approximately 0.03 cm per measurement point (Keller and Ostry, 1983; and Munhall and Ostry, 1985).

IV. MEASUREMENTS

For analysis purposes, each VCV sequence was examined in terms of the VC and CV gestures. The amplitude, duration and movement start time relative to specific acoustic events were calculated for each gesture. In Fig. 3 (top panel), the distance from the transducer to the lateral

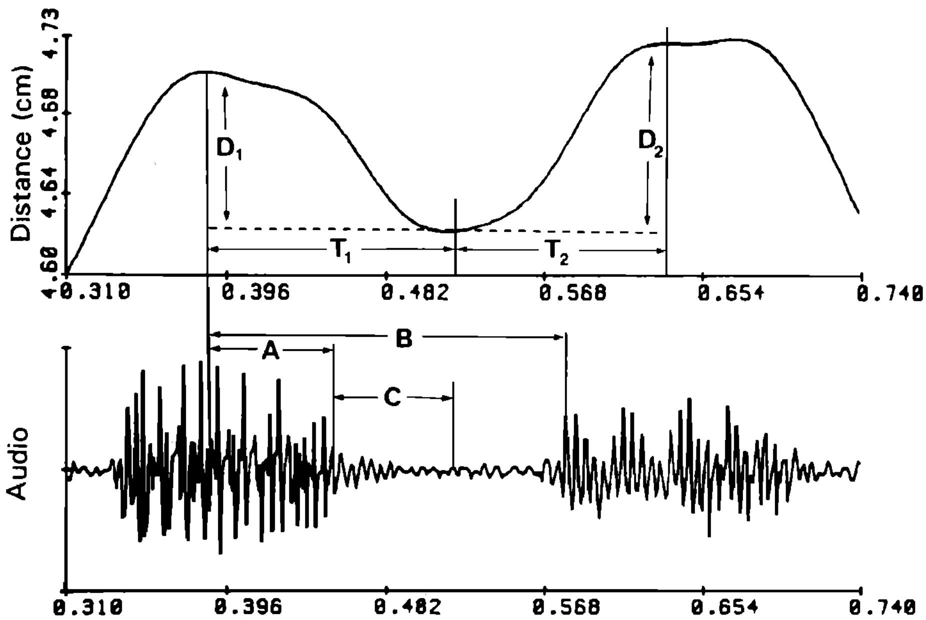

FIG. 3. Distance of the lateral pharyngeal wall from the ultrasound transducer and the corresponding acoustic waveform for a single VCV sequence. ($D1$ and $D2$ indicate distance or movement amplitude; $T1$ and $T2$ indicate duration; A, B, and C indicate the onset of movements relative to acoustic events.)

pharyngeal wall is plotted against time for the VCV sequence /ɑpɑ/. $D1$, the distance moved from the initial vowel to the intervocalic consonant, was calculated as the absolute value of distance between the zero-velocity point for the initial vowel and the zero-velocity point during the consonant oral closure. $T1$, the duration of the initial VC gesture, was calculated as the time interval between the two zero-velocity points. $D1$ and $T1$ were assessed as a function of the final vowel and thus provided spatial and temporal measures of anticipatory coarticulation. It should be noted that the pharyngeal wall did not always reach zero velocity during the consonant production. In such cases, the point of minimum velocity was taken as the position for the consonant. Thus, two different criteria were used as an index of consonant position.

The interval between the zero-velocity point for the initial vowel and the implosion of the intervocalic consonant, shown in Fig. 3 as interval A, provided a further index of anticipatory coarticulation. Longer intervals indicated earlier movement onsets relative to consonant implosion. In a another measure of anticipatory coarticulation, the start of pharyngeal movement away from the initial vowel was examined relative to the voice onset of the final vowel, shown in Fig. 3 as interval B. Both intervals A and B were used to assess the effects of the final vowel on the initiation of movement away from the initial vowel. Thus, intervals A and B provided measures of anticipatory coarticulation based on both acoustical and kinematic events. The timing of acoustical events was measured using an interactive graphical display program. For scoring purposes, consonant implosion was defined as the end of the periodic sound pressure signal.

The amplitude, duration, and onset of the pharyngeal gesture between the consonant and the final vowel are also shown in Fig. 3. $D2$, the CV amplitude, was calculated as the absolute value of the distance between the zero-velocity position during the consonant production and the zero-velocity position for the final vowel. $T2$, the CV duration was calculated as the time interval between these two zero-velocity positions. In addition, the onset of the final CV gesture was examined relative to the implosion of the intervocalic consonant, shown in Fig. 3 as interval C. This interval was used to examine the effect of the final vowel on the onset time, during the consonant closure, of the movement toward that vowel. $D2$ and $T2$ were assessed as a function of the initial vowel in order to obtain measures of carryover coarticulation. Interval C, provided a temporal measure of coarticulation based on the start time of movement to the final vowel during consonant closure.

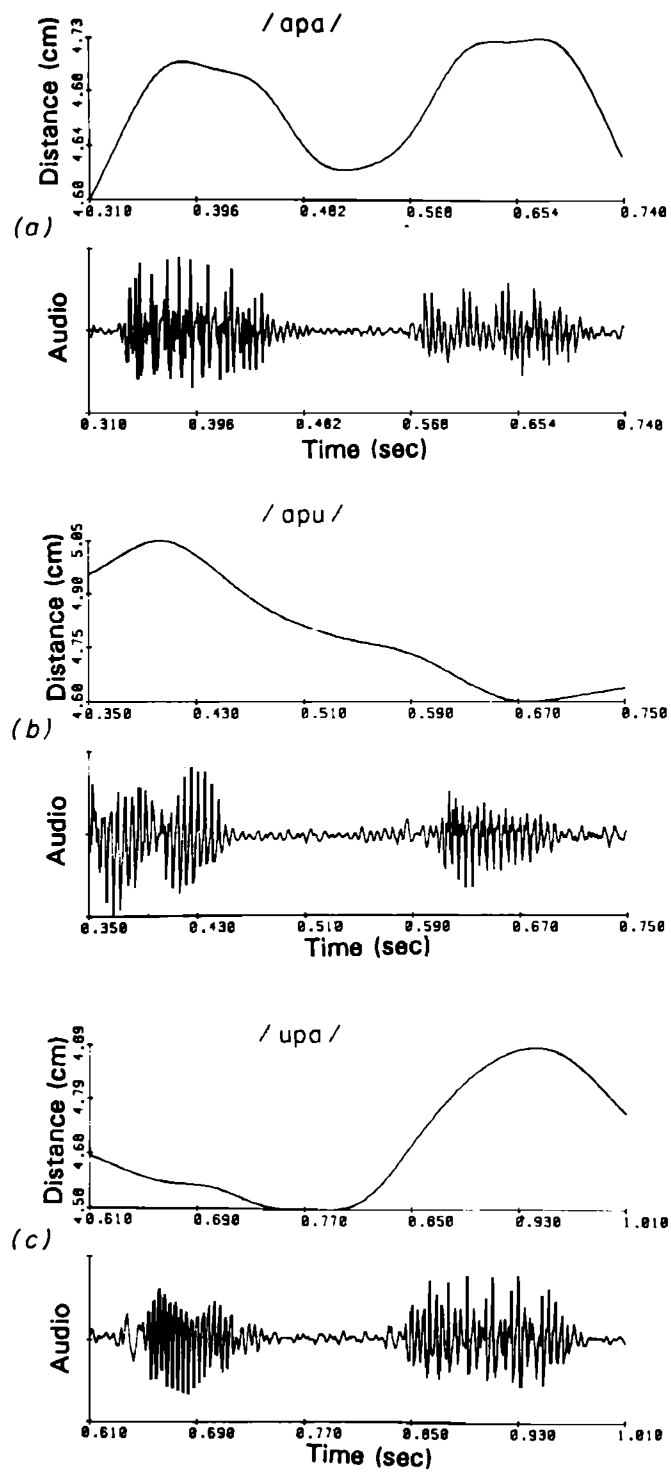

FIG. 4. Lateral pharyngeal wall movements and the corresponding speech waveform for VpV sequences: /ɑpɑ/ (a); /ɑpu/ (b); /upɑ/ (c). (The units on the ordinates correspond to the distance between the transducer and the lateral pharyngeal wall.)

V. RESULTS

A. Overall characteristics

As in previous reports, we observed a larger amplitude inward directed or medial movement of the lateral pharyngeal wall for low back vowels (narrow pharyngeal cavity) and a smaller amplitude inward movement for high vowels (wide pharyngeal cavity). The width of the pharynx was observed to increase for voiceless stop consonants such as /p/ and /k/ (e.g., Perkell, 1969). Figure 4 is an illustrative example of the lateral pharyngeal wall movements observed in this study. Note that whereas most vowel related lateral pharyngeal wall movements are in an inward or medial direction, in some cases lateral or outward directed vowel-related movements are observed [Fig. 4(b)].

The distance from the transducer to the pharyngeal

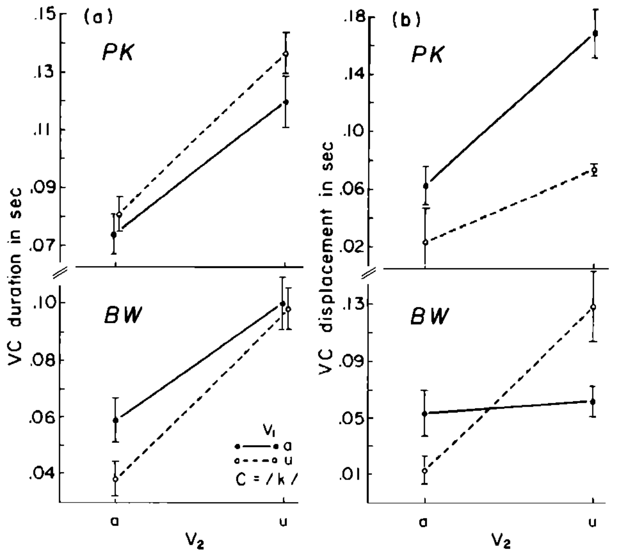

FIG. 5. The mean duration (a) and amplitude (b) of the pharyngeal VC gestures. The consonant shown is /k/. ±1 standard error is indicated.

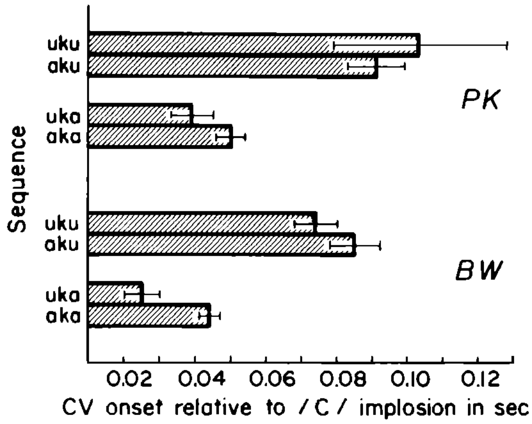

FIG. 6. The mean interval between the movement onset of the pharyngeal CV gesture and the implosion of the consonant, for each of four VkV types. ±1 standard error is indicated.

wall and the corresponding speech waveform are shown in Fig. 4 for VpV utterances that include the vowel /ɑ/. In Fig. 4(a) the sequence is /ɑpɑ/, /ɑpu/ in Fig. 4(b), and /upɑ/ in Fig. 4(c). In all three sequences it can be seen that there was greater absolute movement amplitude for /ɑ/ than for /u/. Pharyngeal wall retraction or relaxation accompanied the intervocalic consonant /p/. A similar pattern was observed for the VCV sequences with the consonant /k/.

The amplitude of the CV gesture associated with the vowel /u/ was significantly less than the amplitude associated with the vowel /ɑ/ [$F(1,68)=327, p<0.001$, for both consonants, for subject PK, and $F(1,46)=98$, $p<0.001$, for the consonant /p/, for subject BW]. The CV movement amplitude in the sequences /uku/ and /upu/ was the smallest, for both subjects.

B. Anticipatory coarticulation

1. Movement amplitude and duration

In order to assess anticipatory effects in lateral pharyngeal wall movements, the amplitude and duration of the VC gesture were examined as a function of the final vowel. These effects were tested in a three-way ANOVA (2 initial vowels×2 final vowels×2 consonants) in which the VC amplitude and duration were used as dependent variables. Significant variations in VC amplitude and duration were observed as a function of the final vowel.

Figure 5 shows the VC duration ($T1$ in Fig. 3) and movement amplitude ($D1$ in Fig. 3) as a function of the final vowel for each of the initial vowels when C=/k/. With the exception of movement amplitude for /ɑku/ vs /ɑkɑ/ for BW, it can be seen that both duration and distance from the initial vowel to the position during consonant production increased as the final vowel shifted from low to high. Kelsey *et al.* (1969) have also shown that the pharyngeal wall movements during /ɑ/ vary as a function of the phonetic context.

The reduced duration of the VC gesture when the final vowel is /ɑ/ can also be expressed in terms of the onset time of the gesture from the consonant position toward the final vowel, during the consonant closure (indexed by interval C in Fig. 3). The movement onset times of the CV gesture relative to the /k/ implosion are shown in Fig. 6, for each of the four sequences. Note, again that this interval enables the examination of the effect of the final vowel on the start time during consonant closure of the movement toward that vowel. There was a significant variation in the interval between the CV movement onset point and the consonant implosion as a function of the final vowel, for both subjects [$F(1,68)=20.6$, $p<0.01$ for subject PK and $F(1,85)=93.3$, $p<0.01$ for subject BW]. It can be seen in Fig. 6 that movements towards the vowel /ɑ/ started earlier, indicated by the shorter intervals, than movements toward /u/. Note, that only data for /k/ are presented here since, in general, there was less intersubject variability for /k/ than for /p/.

2. Movement onset

The onset time of the gesture away from the initial vowel was examined as a function of the final vowel. This provided a temporal measure of anticipatory coarticulation. The movement onset points were assessed relative to the implosion point of the intervocalic consonant, and relative to the voice onset of the final vowel, shown as intervals A and B, respectively, in Fig. 3.

The VC movement onset times relative to the /k/ and /p/ implosion are shown in Fig. 7, for each of the four sequences. There was a significant difference in the movement onset time between the two consonants, for both subjects [$F(1,68)=8.3$, $p<0.01$ for subject PK, $F(1,85)=68.5$, $p<0.01$ for subject BW]. This interval (A in Fig. 3) did not vary significantly as a function of the final vowel, for either subject. Overall, it can be seen that the VC gestures started earlier when the intervocalic consonant was /p/ rather than /k/, indicated by longer intervals, regardless of the vocalic context.

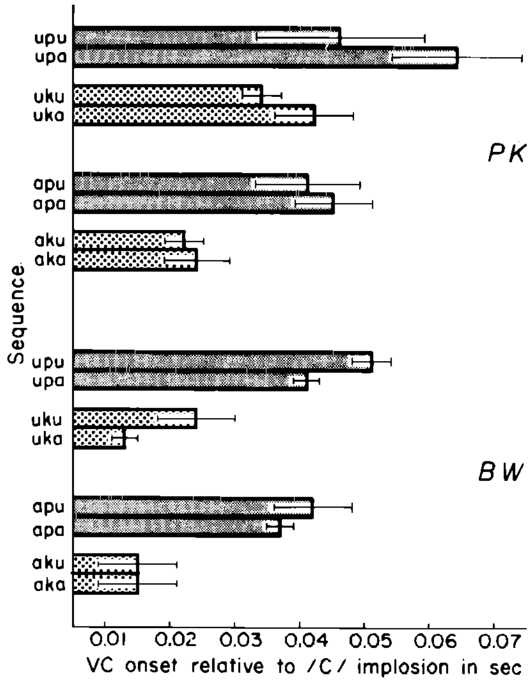

FIG. 7. The mean interval between the movement onset of the pharyngeal VC gesture and the implosion of the consonant, for each of the eight VCV types. ±1 standard error about each mean is shown.

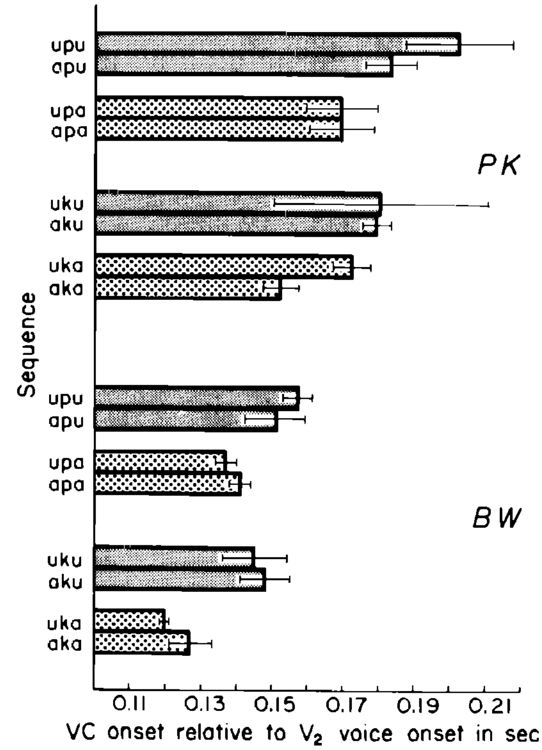

FIG. 8. The mean interval between the onset of the pharyngeal VC gesture and the voice onset of the final vowel, for each of eight VCV types. Standard errors are shown.

Perkell (1969) presented some evidence that the pharyngeal cavity begins to widen later for /p/ than /k/. However, his analysis was based on a single token of each utterance and the utterance materials were different from the ones reported here. The discrepancy between Perkell's observation and the results reported here may also be due to the different measurements used in the two studies. Perkell (1969) measured pharynx width by monitoring the horizontal movements of the tongue dorsum, while pharynx width was measured here by monitoring lateral pharyngeal wall movements.

The onset of the movement away from the initial vowel was also examined relative to the voice onset of the final vowel (interval B in Fig. 3). This onset time is shown in Fig. 8, for all sequences. Overall, the onset time was affected by the final vowel, with earlier onsets for movements toward /u/ than /ɑ/, regardless of the intervocalic consonant [$F(1,68)=8.8$, $p<0.01$ for subject PK and $F(1,85)=41.6$, $p<0.01$ for subject BW].

C. Carryover coarticulation

In order to assess the carryover effects in the lateral pharyngeal wall movements, the movement amplitude and duration of the gesture from the consonant to the final vowel, were examined as a function of the initial vowel. The amplitude of the CV gesture varied significantly as a function of the initial vowel when the consonant was /k/ [$F(1,68)=115$, $p<0.01$ for PK, $F(1,85)=30.5$, $p<0.01$ for BW]. These patterns are displayed in Fig. 9 for the CV sequence /kɑ/. It can be seen that the final CV amplitude increased as the initial vowel shifted from low to high.

The CV duration varied significantly as a function of the initial vowel only for subject BW, [$F(1,46)=19.5$, $p<0.01$]. The duration of the CV gesture was shorter when the initial vowel was /ɑ/.

VI. DISCUSSION

Both anticipatory and carryover coarticulation were observed in lower lateral pharyngeal wall movements. The anticipatory effects were both spatial and temporal in na-

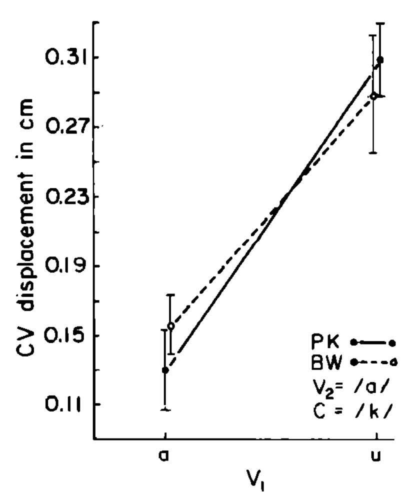

FIG. 9. The mean amplitude of the pharyngeal /kɑ/ gesture for the two initial vowels. ±1 standard error is indicated.

ture. The carryover effects were spatial for both subjects; only one subject (BW) showed temporal carryover effects.

Vowel related movements of the lower pharyngeal walls were observed in the present study. The magnitude of the lower pharyngeal constriction depends on the identity of the back vowel. The pharynx is more constricted for low vowels and less constricted for high vowels (e.g., Perkell, 1969; Kent and Moll, 1969; Wood, 1979). Pharyngeal wall positions for consonants have been shown by other researchers to vary as a function of the vocalic context (Perkell, 1969; Zagzebski, 1975) and with individual differences (e.g., Johansson *et al.*, 1984).

It was observed that when the initial vowel was held constant, the pharyngeal position during the consonant was affected by the position of the pharynx required for the final vowel. For example, when the final vowel was /ɑ/, the consonant was articulated with a more narrow pharynx, whereas, when the final vowel was /u/, the consonant was produced with a more open pharynx. Consequently, the amplitude of the initial VC transition was affected by the identity of the final vowel. Similarly, the amplitude of the final CV transition was affected by the initial vowel. When the initial vowel was /ɑ/, the consonant was produced with a more narrow pharynx than when the initial vowel was /u/. This affected the magnitude of the transition from the consonant to the final vowel.

The effects of movements between vowels on pharyngeal position during the consonant production were also seen in the temporal measures. The onset time of the gesture away from the initial vowel was related to the final vowel. The movement started earlier, relative to the voice onset of the final vowel, when the vowel was /u/. In addition, the duration of the VC gesture was affected by the position of the pharynx during consonant production. When the consonant was produced with a more narrow cavity (e.g., when the final vowel was /ɑ/), the duration of the gesture from the initial vowel to the consonant was shorter. The finding that the consonant position was reached earlier when the final vowel was /ɑ/ is reflected in the interval between the position for the consonant oral closure and the position for the vowel. Overall, the temporal aspects of the movement away from the initial vowel were related to the identity of the final vowel.

One must be careful about making generalizations from a small set of nonsense utterances produced by two subjects. Nevertheless, it may be noted that the basic kinematic patterns reported here for the lower pharynx are similar to those that we have reported previously for tongue and upper pharyngeal wall coarticulation (Parush *et al.*, 1983; Parush and Ostry, 1986).

In each of these studies, anticipatory effects were assessed by holding constant the identity of the initial vowel in a VCV sequence and varying the identity of the final vowel. Thus we were able to examine the amplitude and duration of the initial VC transition as a function of the amplitude of the movement from the consonant to the final vowel. In all three articulators, we found that the magnitude and duration of the initial VC transition was greater when a small amplitude movement was required from the consonant to the final vowel (e.g., /ɑCu/ vs /ɑCɑ/ for the tongue dorsum). A very similar pattern was observed for carryover effects. We found that, in all articulators, the amplitude of the movement from the consonant toward the final vowel was greater when small amplitude movement was required for the initial VC transition (e.g., /uCɑ/ vs /ɑCɑ/ for the tongue dorsum).

The similarity of the present findings to those of our two previous ultrasound studies (Parush *et al.*, 1983; Parush and Ostry, 1986) suggests that coarticulation reflects a rather basic process associated with orofacial motions. In this context, we will consider two general classes of models that have been suggested to account for coarticulation: The "look-ahead" model (e.g., Henke, 1966) and the coproduction model (Ohman, 1966; Fowler, 1980; also see Bell-Berti and Krakow, 1991). We will focus on the extent to which features of upcoming movements are taken into account in planning the current movement.

According to the coproduction view, coarticulation reflects the superposition of gestures as a result of temporal overlap in their production. This permits a rather simple control scheme in which intraarticular coarticulation can be described as the result of the superposition of independent central commands (Munhall and Löfqvist, 1992). Mathematical formulations of schemes such as this have been successful in predicting the kind of kinematic blending which is observed in speech coarticulation (Flash and Henis, 1991; Flanagan *et al.*, in press).

Alternatively, the acoustical goals of speech production may require modification to the simple superposition rule, for example, in cases where strict superposition would distort speech. In such situations, central commands for individual gestures would have to take account of upcoming motions and the acoustical consequences of superposition. This is an essential notion of look-ahead views of coarticulation. The need to consider context may depend on factors such as the position of the articulators in the oral cavity in combination with the magnitude and direction of the required orofacial motions.

ACKNOWLEDGMENTS

This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada and the Fond pour la formation de chercheurs et l'aide à la recherche (FCAR) program of Québec. The authors thank Fredericka Bell-Berti, Suzanne Boyce, and Joe Perkell for their reviews.

Bell-Berti, F. (1971). "The velopharyngeal mechanism: An electromyographic study—A preliminary report," Haskins Laboratories Status Report on Speech Research, SR-25/26, 117–129.

Bell-Berti, F., and Krakow, R. (1991). "Anticipatory velar lowering: A co-production account," J. Acoust. Soc. Am. 90, 112–123.

Flanagan, J. R., Ostry, D. J., and Feldman, A. G. (1993). "Control of trajectory modifications in target-directed reaching," J. Motor Behavior (in press).

Flash, T. and Henis, E. (1991). "Arm trajectory modification during reaching towards visual targets," J. Cognitive Neurosci. 3, 220–230.

Fowler, C. A. (1980). "Coarticulation and theories of extrinsic timing," J. Phonetics 8, 113–133.

Fritzel, B. (**1969**). "The velopharyngeal muscles in speech," Acta Oto-Laryngol. Suppl. 250.

Henke, W. L. (**1966**). "Dynamic articulatory model of speech production using computer simulation," Unpublished doctoral dissertation, Massachusetts Institute of Technology.

Johansson, C., Sundberg, J., and Wilbrand, H. (**1984**). "From sagittal distance to area: A study of pharyngeal cross-sectional area of computer tomography," J. Acoust. Soc. Am. Suppl. 1 **75**, S22.

Johnson, L. W., and Riess, R. D. (**1977**). *Numerical Analysis* (Addison-Wesley, Reading, MA).

Keller, E., and Ostry, D. J. (**1983**). "Computerized measurement of tongue dorsum movement with pulsed-echo ultrasound," J. Acoust. Soc. Am. **73**, 1309–1315.

Kelsey, C. A., Minifie, F. D., and Hixon, T. J. (**1969a**). "Applications of ultrasound in speech research," J. Speech Hear. Res. **12**, 546–575.

Kelsey, C. A., Woodhouse, R. J., and Minifie, F. D. (**1969b**). "Ultrasonic observations of coarticulation in the pharynx," J. Acoust. Soc. Am. **46**, 1016–1018.

Kent, R. D., and Moll, K. L. (**1969**). "Vocal tract characteristics of the stop cognate," J. Acoust. Soc. Am. **46**, 1549–1555.

Lindquist, J., and Sundberg, J. (**1971**). *Pharyngeal Constrictions* (Speech Transmission Laboratory, Institute of Technology, Stockholm, Sweden), pp. 26–31.

Minifie, F. D., Abbs, J. H., Tarlow, A., and Kwaterski, M. (**1974**). "EMG activity within the pharynx during speech production," J. Speech Hear. Res. **17**, 497–504.

Minifie, F. D., Hixon, T. J., Kelsey, C. A., and Woodhouse, R. J. (**1970**). "Lateral pharyngeal wall movement during speech production," J. Speech Hear. Res. **13**, 584–594.

Munhall, K. G., and Löfqvist, A. (**1992**). "Gestural aggregation in speech: Laryngeal gestures," J. Phonetics **20**, 111–126.

Ohman, S. E. G. (**1966**). "Coarticulation in VCV utterances: Spectrographic measurements," J. Acoust. Soc. Am. **39**, 151–168.

Ostry, D. J., Keller, E., and Parush, A. (**1983**). "Similarities in the control of the speech articulators and the limbs: Kinematics of tongue dorsum movement in speech," J. Exp. Psychol. Human Percept. Performance **9**, 622–636.

Ostry, D. J., and Munhall, K. G. (**1985**). "Control of rate and duration of speech movements," J. Acoust. Soc. Am. **77**, 640–648.

Parush, A., and Ostry, D. J. (**1986**). "Superior lateral pharyngeal wall movements in speech," J. Acoust. Soc. Am. **80**, 749–756.

Parush, A., Ostry, D. J., and Munhall, K. G. (**1983**). "A kinematic study of lingual coarticulation in VCV sequences," J. Acoust. Soc. Am. **74**, 1115–1125.

Perkell, J. S. (**1969**). *Physiology of Speech Production: Results and Implications of a Quantitative Cineradiographic Study*, Research Monograph No. 53 (MIT, Cambridge, MA).

Perkell, J. S., and Nelson, W. L. (**1982**). "Articulatory targets and speech motor control: A study of vowel production," in *The Motor Control of Speech*, edited by S. Grillner, A. Persson, B. Lindblom, and J. Lubker (Pergamon, New York).

Smith, T. (**1971**). "A phonetic study of the function of extrinsic tongue muscles," UCLA Working Papers in Phonetics 18, University of California at Los Angeles, Department of Phonetics.

Stevens, K. N. (**1972**). "The quantal nature of speech: Evidence from articulatory-acoustic data," in *Human Communication, a Unified View*, edited by P. B. Denes and E. E. David (McGraw-Hill, New York), pp. 51–66.

Wood, S. (**1979**). "A radiographic analysis of constriction locations for vowels," J. Phonetics **7**, 25–43.

Zagzebski, J. A. (**1975**). "Ultrasonic measurement of lateral pharyngeal wall motion at two levels in the vocal tract," J. Speech Hear. Res. **18**, 308–318.