361

Temporal patterns of coarticulation: Lip rounding[a)]

Fredericka Bell-Berti

St. John's University, Jamaica, New York 11439 and Haskins Laboratories, New Haven, Connecticut 06510

Katherine S. Harris

The Graduate School, The City University of New York, New York, New York 10036 and Haskins Laboratories, New Haven, Connecticut 06510

(Received 1 June 1981; accepted for publication 6 October 1981)

According to some theories, anticipatory coarticulation occurs when phones for which a feature is unspecified precede one for which the feature is specified, with consequent migration of the feature value to the antecedent phones. Carryover coarticulation, on the other hand, is often attributed to "articulatory sluggishness." In this paper, EMG evidence is provided that this formulation is inadequate, since the beginning of EMG activity associated with vowel lip rounding is independent of measures of the acoustic duration of adjacent lingual consonants. We suggest that the vowel-rounding gesture simply co-occurs during predictable intervals with portions of preceding and following lingual consonant articulations.

PACS numbers: 43.70.Bk, 43.70.Ve

INTRODUCTION

A central problem in understanding the relationship between speech production and perception is the disparity between the perceptual representation of speech as a series of discrete events, composed of partially commutable elements, and the acoustic representation as a continuously varying stream, without obvious segment markers. This acoustic stream is generated by the activity of the several articulators, whose activity is apparently continuous and context dependent. Many theories of coarticulation attempt to solve the problem of context sensitivity by positing some kind of speech synthesis process which occurs in production, and allows the fitting together of the discrete units into the continuous stream. The task of the theorist, then, is to write the adjustment rules.

In a widely cited theory of anticipatory coarticulation, Henke (1966) provides a fairly typical formulation. Each phone in an articulatory string is conceived as composed of a bundle of articulatory features. Anticipatory coarticulation occurs when phones for which a given feature is unspecified precede one for which the feature is specified, with consequent subjection of the antecedent phones to the feature value of the following phone. Since time is unspecified in the theory, the temporal duration occupied by the string of antecedent phones is presumably irrelevant; all will acquire the same feature value.

It has been claimed by Fowler (1980) that all such theories of coarticulation belong to the class of extrinsic timing models of speech production. Such models assume that the dimension of time is excluded from the specification of a phonological segment in the motor plan for the utterance. In Fowler's view, such accounts must therefore necessarily fail to explain or predict coarticulation. While one may or may not accept her argument in its larger theoretical framework, we believe that purely substantive evidence can be marshaled against such phonological segment theories as a class.

In an earlier report (Bell-Berti and Harris, 1979) we provided evidence that this formulation is inadequate, and have elsewhere suggested an alternative hypothesis (Bell-Berti, 1980; Bell-Berti and Harris, in press). Specifically, we found that if a rounded vowel was preceded by one or two consonants presumably unspecified for rounding, the electromyographic activity associated with rounding began a constant time, rather than a constant number of segments, before the onset of the vowel.

The present experiment was designed to extend the earlier one in several ways. First, we have examined both anticipatory and carryover coarticulation of lip rounding. Often, "articulatory sluggishness" explanations are proposed for carryover coarticulation while "planning" explanations are proposed for anticipatory coarticulation (e.g., MacNeilage, 1970). However, if both anticipatory and carryover effects appear to be guided by the same articulatory rules, disparate explanations for these two effects seem less plausible.

Secondly, we have examined the special case in which coarticulation occurs from one vowel to another vowel, where both vowels are rounded and are separated by intervening consonants without rounding specification. In such cases, it has been shown that a "trough" will occur—that is, EMG "rounding activity" will be reduced at some point in the period between vowels. This situation is, of course, not explicable by the type of model of coarticulation exemplified by Henke's, as we (Bell-Berti and Harris, 1974) and others (e.g., Gay, 1978) have pointed out.

Thirdly, we extended the design of the experiment to include longer strings of consonants preceding or following the rounded vowel than the original maximum of two-element clusters. We also increased the subject pool, and included subjects naive to the purposes of the experiment.

[a)]Some of these data were presented at the 96th Meeting of the Acoustical Society of America, Honolulu, HI, November 1978 [J. Acoust. Soc. Am. Suppl. 1 64, S92 (1978)] and at the 97th Meeting of the Acoustical Society of America, Cambridge, MA, June 1979 [J. Acoust. Soc. Am. Suppl. 1 65, S22(1979)].

© 1982 Acoustical Society of America

Fourthly, we checked the subjects to see if rounding activity occurred for segment sequences for which no lip rounding was specified. In a theory like Henke's, it is assumed that a feature such as lip rounding spreads from a phone for which it is specified to the preceding phones for which it is not. If the preceding phones carry a specification for the feature, the experiment provides no test of the theory. Earlier studies (Daniloff and Moll, 1968) have been criticized by later authors (Benguerel and Cowan, 1974) for possible design flaws of this type. For the experiment described here, we assume that the alveolars, especially /s/, are neutral with respect to rounding. Hence, we would expect that in sequences of the form /isi/, no EMG evidence of rounding would be observed, since the vowel /i/ is traditionally characterized as spread and the consonant /s/ is not traditionally characterized with respect to lip rounding (Bronstein, 1960). However, traditional descriptions are often enough incomplete as to fine-grained articulatory detail that it seemed worthwhile to make an explicit check of lip activity during the sequence /isi/ for each speaker.

As in the previous study, we have used an electromyographic indicator of rounding, the activity of the orbicularis oris muscle. The relationship between orbicularis oris activity and vowel rounding is well documented by a number of studies (Harris *et al.*, 1965; Fromkin, 1966; Tatham and Morton, 1968; Sussman and Westbury, 1981).

I. METHODS

A. Speech materials

The experimental speech materials were two-word phrases spoken within the carrier phrase "It's a ______ again." The first word was one from the set "lee, lease, leased, loo, loose, loosed," while the second word was one from the set "tool, stool, teal, steel." All utterances whose second word was either "tool" or "stool" will be called the "anticipatory" set in the discussion below, since they were designed to examine anticipatory lip rounding. Conversely, those utterances whose first word was "loo," "loose," or "loosed" and whose second word was "teal" or "steel" will be called the "carryover" set.

In addition to these 18 experimental utterances (12 in the anticipatory and six in the carryover sets), we examined an additional group that included "lee teal" and "lee seal," to determine whether a speaker produced either or both of the alveolar consonants /t/ or /s/ with orbicularis oris EMG activity, in the absence of a rounded vowel.

The experimental utterances were placed in randomized lists which included additional items intended as foils. Five subjects read the randomized lists until 14 to 18 repetitions of each experimental utterance had been recorded. A sixth subject produced only 10 repetitions of each utterance type. Subjects were asked to read the sentences from an orthographic representation, and thus produced the phonetic sequences natural to the word combinations—e.g. [listul] rather than [list tul] for "leased tool."

B. Subjects

Five of the six subjects of the experiment were naive to its purposes; one subject (FBB) was a subject in the previous study. Three of the five naive subjects showed activity in orbicularis oris associated with the production of /s/ in spread vowel environments; hence, their data were not further analyzed. All of the subjects whose data are presented here are speakers of educated greater metropolitan New York City English.

C. EMG and audio data collection

EMG potentials were recorded from several placements on the superior and inferior orbicularis oris muscles for each subject, using surface electrodes similar to those described by Allen, Lubker, and Harrison (1972). The electrodes were applied to the vermilion border of the lips, and spaced about $\frac{1}{2}$-cm apart. The EMG signals were recorded simultaneously with the audio and clock signals on a multichannel FM tape recorder. In later analyses, the channel yielding the EMG signal with the largest amplitude was chosen; in all cases, this was a superior lip placement. Signals from the lower lip placements did not appear to be qualitatively different, but had a lower signal-to-noise ratio.

1. Acoustic measurements

The acoustic recordings from each of the three subjects whose data were subjected to detailed analysis were digitized and analyzed using an oscillographic display of the digitized waveform. For each of the 18 two-word test utterances, the durations of the /lV/ and /Vl/ sequences were measured for each of the 10 to 18 repetitions, as were the durations of /s/ friction and /t/ closure and aspiration. Average durations of the /lV/,

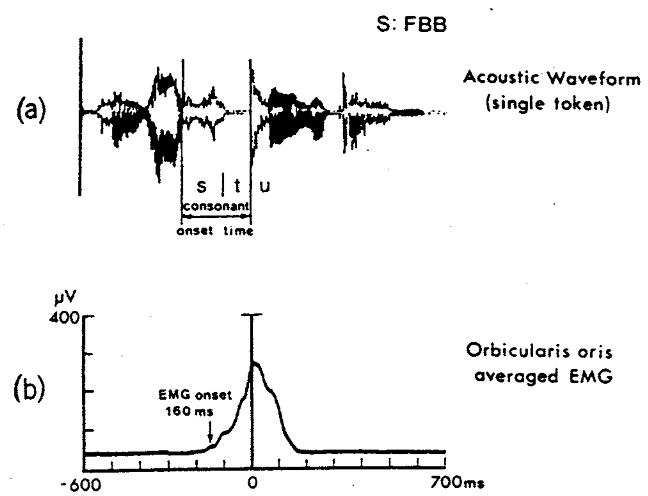

FIG. 1. (a) Sample waveform of one token of the utterance type "lease tool" for subject FBB, with consonant onset time (consonant–string duration) indicated. (b) Ensemble-average EMG activity from the orbicularis oris muscle, for all tokens of "lease tool," for subject FBB. EMG onset time, at 5% of baseline-to-peak amplitude, is indicated at 160 ms before /t/ release.

/Vl/, and consonant sequences were calculated from the individual token measurements.

Reference points were chosen for aligning tokens of each utterance type for later sampling and averaging of the EMG potentials. The point chosen for the 12 members of the anticipatory set was the release of the /t/ before /u/; for the carryover set, it was the moment of /t/ closure or the beginning of /s/ friction immediately after /u/ [Fig. 1(a)].

2. *EMG measurements*

The EMG waveforms for each electrode position (channel) and utterance repetition were rectified, integrated (5-ms hardware integration), and digitized. The signals were smoothed using a 35-ms triangular window, and the ensemble average was calculated for each utterance and channel from the integrated EMG waveforms,[1] after aligning all tokens at the reference point in the acoustic waveform. These signal recording and processing techniques have been described in detail elsewhere (Kewley-Port, 1973).

Using the ensemble averages, we determined the beginning of orbicularis oris activity for the utterances in the anticipatory set, and the end of this activity for the utterances in the carryover set. For the anticipatory set utterances, the beginning of activity was defined as the time at which orbicularis oris EMG activity reached 5% of its maximum amplitude.[2] An example of an ensemble average of one utterance, from the data of subject FBB, is shown in Fig. 1(b), with this onset time indicated. For the carryover set, the end of activity was defined as the time at which orbicularis oris EMG activity fell to 5% of its maximum amplitude.

II. RESULTS

A. Anticipatory coarticulation

If the beginning of vowel rounding activity were linked to the beginning of the preceding consonant string, then regardless of the number of consonants in the string, this activity should begin earlier when the consonant string is of longer duration. If, on the other hand, the beginning of the orbicularis oris activity were linked to the presence of a rounded vowel, there should be no correlation between the timing of the beginning of EMG activity and the duration of friction and closure. Since there is a general tendency for these events to be of shorter duration in clusters, it is necessary to examine a number of different consonant sequences, of different lengths, in order to test consonant-linked versus vowel-linked onset. In the present set, the acoustic durations of the medial sequences ranged from 70 to about 420 ms.

The "onset time" of orbicularis oris EMG activity relative to consonant-string duration is shown for the utterances of the /i–u/ anticipatory set in the left-hand column of Fig. 2. Each panel shows the data for one of the three subjects; each point represents the average consonant-string duration and EMG onset time for about 14 tokens of each type for two subjects and 10 tokens of each type for the third. If anticipatory coarticulation were systematically related to the onset of the consonant string, we would expect the points to be fitted by a line having a positive slope; instead, however, the points are fitted by a line whose slope is not significantly different from zero in two cases, and is significantly negative in the third (Table I).

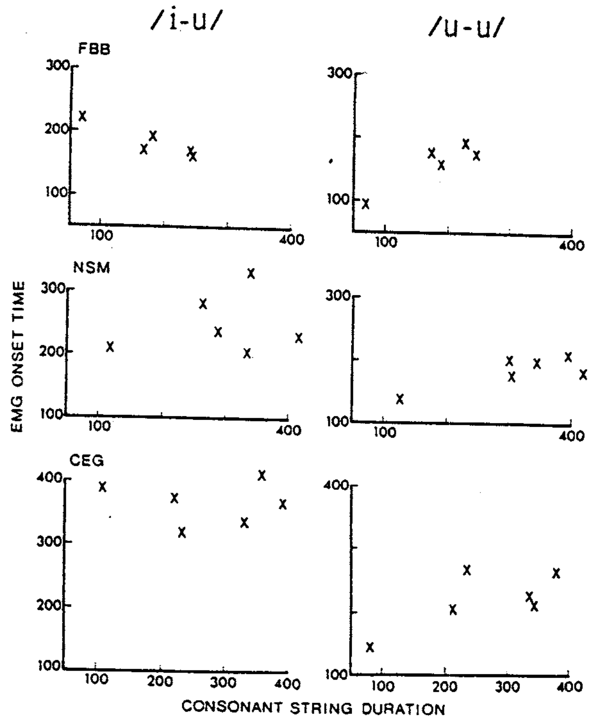

FIG. 2. Scatter plots of consonant-string duration versus EMG onset time in ms for anticipatory set utterances, for all three subjects. /i–u/ utterance data are presented in the left-hand column; /u–u/ utterance data are presented in the right-hand column.

In the right-hand part of Fig. 2, we have plotted the EMG onset time relative to consonant string duration for the /u–u/ utterances. The results fit the same general description as the /i–u/ case; that is, coarticulation began a constant interval before the onset of the second vowel, with a single exception for each of the three speakers—the case having the shortest consonant duration. A fairly straightforward explanation can be provided, if we assume that for this case the intervocalic interval may be shorter than the time necessary for muscle activity to fall to baseline for the first /u/ and rise for the second. This hypothesis is supported by the fact that, for all three subjects, the minimum, or baseline, activity for /t/ strings is higher than for any other (Table II).

Another interesting result of the two-vowel conditions is that there is a difference in the level of the best straight-line fit for /i–u/ and /u–u/ cases; that is, rounding for the second vowel begins earlier if the first vowel was /i/ than if it was /u/. Somewhat similar data are presented by Sussman and Westbury (1981) for /i–u/ sequences as contrasted with /a–u/ sequences. In their data, the difference in onset time is not significant for the /ikstu/ versus /akstu/ comparison, although the difference in onset time is significant for the /iku/ versus

TABLE I. A. Anticipatory coarticulation. B. Carryover coarticulation.

A. Anticipatory coarticulation: Slope of best-fit line for consonant-string duration versus EMG onset time for /i–u/ and /u–u/ utterances.

	FBB	NSM	CEG
/i–u/	$m = -0.3209$	$m = 0.1049$	$m = 0.0006$
	$^{a}F_{1,3} = 19.49$	$F_{1,4} = 0.20$	$F_{1,4} = 0.000014$
/u–u/	$m = 0.4927$	$m = 0.1953$	$m = 0.2899$
	$^{b}F_{1,3} = 13.47$	$F_{1,4} = 7.21$	$F_{1,4} = 4.34$

B. Carryover coarticulation: Slope of best-fit line for consonant-string duration versus EMG offset time for /u–i/ and /u–u/ utterances.

	FBB	NSM	CEG
/u–i/	$m = 0.0161$	$m = 0.0674$	$m = 0.4295$
	$F_{1,5} = 0.3249$	$F_{1,4} = 4.66$	$^{c}F_{1,4} = 10.74$
/u–u/	$m = -0.0566$	$m = 0.0162$	$m = -0.3843$
	$F_{1,3} = 0.1089$	$F_{1,4} = 0.2152$	$^{d}F_{1,4} = 23.42$

[a] $p < 0.05$, but slope is negative.
[b] $p < 0.05$. If /utu/ case not included, $m = 0.1544$, $F_{1,2} = 0.27$ ($p > 0.05$).
[c] $p < 0.05$.
[d] $p < 0.01$, but slope is negative.

/aku/ comparison. If the differences in onset time are a consequence of the lip position for the first vowel, we might expect consistent amplitude differences for the second vowel, depending on the identity of the first. Such differences were reported by Sussman and Westbury for the /kst/ cases (see their Fig. 3). They do not comment on the /k/ case, where one might expect larger effects. Peak EMG amplitudes for our own data are presented in Table III, and although there is some tendency for peak values for the second vowel to covary with the identity of the first, there is no absolutely consistent result.

The analysis presented in Fig. 2 does not examine possible effects of the location of word boundaries. Indeed, in the classic experiment of Daniloff and Moll, no effects of word boundaries were observed, although some similar experiments have claimed to show effects of some kinds of linguistic boundaries (e.g., McClean, 1973). Since there are complex but systematic effects of word boundaries on consonant duration (Lehiste, 1969), we re-examined the data for possible word-boundary effects, as shown in Fig. 3. It was not possible to examine those utterances produced with a segment common to the end of the first word and beginning of the second because consonant duration could not be apportioned

TABLE II. Minimum EMG amplitude (in μV) during the interval between vowels in /u–u/ utterances.

	FBB	NSM	CEG
t	68	79	114
#st	52	70	67
s#t	48	74	74
st#t	46	70	59
s#st	43	68	62
st#st		69	54

TABLE III. Peak EMG amplitude (in μV) for vowels of second syllable of anticipatory set utterances, with /u–u/ utterances peak amplitude at the left and /i–u/ utterance peak amplitude at the right.

		Peak amplitude /u–u/	Peak amplitude /i–u/
FBB	#t	236	362
	#st	314	301
	s#t	280	265
	st#t	239	269
	s#st	237	270
NSM			
	#t	518	439
	s#t	480	502
	st#t	475	444
	#st	506	507
	s#st	434	452
	st#st	421	430
CEG			
	t	272	222
	s#t	235	246
	#st	228	274
	s#st	207	200
	st#t	190	200
	st#st	240	244

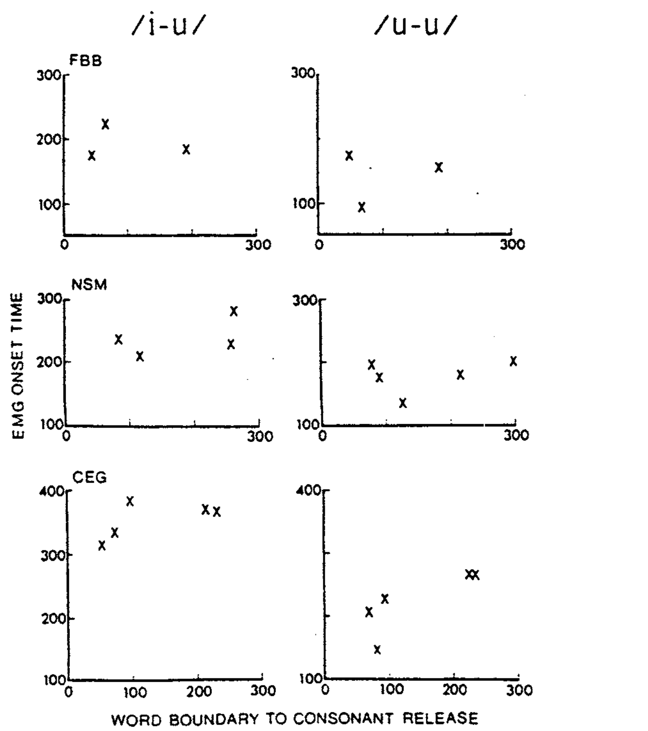

FIG. 3. Scatter plots of the duration of word–initial consonant strings versus EMG onset time in ms, for anticipatory set utterances, for all three subjects. /i–u/ utterance data are presented in the left-hand column; /u–u/ utterance data are presented in the right-hand column.

to one or another side of the word boundary. For example, as noted above, the sequence which was orthographically represented as "leased tool" was usually executed as [listul]; since /t/ was associated with both words, no separation could be made. For the subset of the utterances where an acoustic event could be associated with the word boundary, the results are as before—that is, there is no systematic relationship between onset of anticipatory coarticulation and word boundary (Fig. 3). We would add that for each utterance set for each subject, the range of EMG onset times for the orbicularis oris is considerably smaller than the range of consonant durations (Table IV, part A). If the onset of EMG activity were linked to the beginning of the measured durations, we would expect the ranges to be comparable.

B. Carryover coarticulation

Examining the timing relationship between the end of orbicularis oris EMG activity and the duration of the consonant string following a rounded vowel, we found a pattern very much like that found for the anticipatory condition. Specifically, the "offset time" appears to be unaffected by the duration of the following consonant string (Fig. 4). Rather, the slope of the line of best fit for each utterance set for each subject was not significantly different from zero (Table IB). And again, as with the anticipatory coarticulation data, the range of EMG offset times is smaller than the range of consonant durations (Table IV, part B). In these data, however, lip position for the following vowel did not influence the timing of the end of the vowel gesture. That is, the following vowel is not anticipated in the timing of the end of the first vowel gesture.

TABLE IV. Range, in ms, of EMG onset and offset times and consonant-string durations.

A. Anticipatory coarticulation

		EMG onset	Consonant duration	Syllable initial consonant duration
FBB	iC_nu	55	174	113
	uC_nu	95	172	119
NSM	iC_nu	125	299	176
	uC_nu	70	296	220
CEG	iC_nu	95	281	174
	uC_nu	120	298	166

B. Carryover coarticulation

		EMG offset	Consonant duration	Syllable final consonant duration
FBB	uC_ni	15	235	193
	uC_nu	50	172	123
NSM	uC_ni	25	293	211
	uC_nu	20	296	267
CEG	uC_ni	140	260	252
	uC_nu	110	298	244

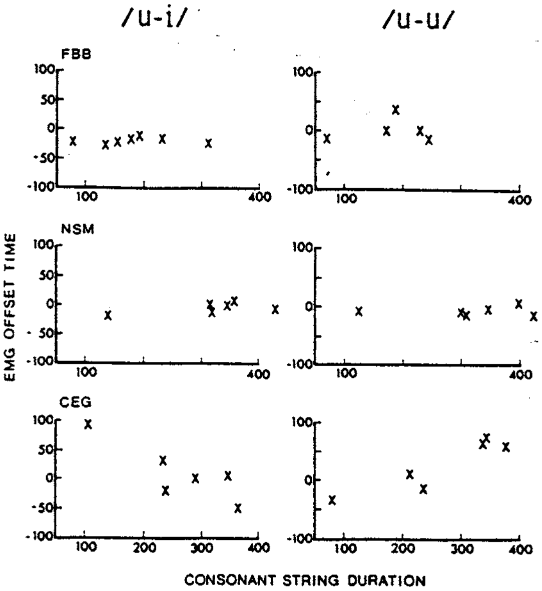

FIG. 4. Scatter plots of consonant-string duration versus EMG offset time in ms, for carryover set utterances, for all three subjects. /u–i/ utterance data are presented in the left-hand column; /u–u/ utterance data are presented in the right-hand column.

III. DISCUSSION

The data suggest that the beginning of EMG activity associated with lip-rounding gestures for vowels is more obviously related to other components of the vowel articulation than to aspects of the consonant-string length. Similarly, the end of EMG activity associated with lip-rounding gestures is most straightforwardly described with relation to the end of the vowel, and not with relation to the following consonant string.

Previously published reports, suggesting that lip-rounding gestures migrate ahead to the beginning of a preceding consonant string, may be accounted for by referring to the timing of orbicularis oris activity for the second vowel in /u–u/ utterances having short-duration consonant strings. In these cases, lip-rounding activity seems to begin later (i.e., closer to the second vowel) than it does in utterances having longer consonant sequences. If one examines only a few utterance types with one or two short and one long consonant sequence (cf. Sussman and Westbury, 1981), and if an earlier vowel gesture either inhibits or masks the beginning of the rounding gesture in the short-string utterances, it may appear as though lip-rounding onset follows the beginning of the preceding consonant string. However, we believe that our data cannot be accounted for in this way, nor can the movement study of Engstrand (1980), which gave the same general picture.

This picture of coarticulation is quite different from the look-ahead scanner model presented by Sussman and Westbury (1981). In their model, if a prior vowel is biomechanically antagonistic to rounding, "temporal and amplitude adjustments are incorporated into the anticipatory rounding gesture." Rounding begins, presumably, some time after the end of the antagonistic vowel, but this time is simply displaced by some amount from the beginning of the intervocalic string. Thus there is always a carryover effect of the preceding vowel on the onset of rounding; but for all consonant strings longer than some value, the onset of rounding varies with string duration, presumably as a reflection of the number of elements in the string. In the model proposed here, a preceding vowel may have some antagonistic effect on the onset of rounding, and hence rounding may appear closer to the second vowel in cases where the consonant string is short, or when the vowel changes. However, rounding onset time does not covary with the number of consonant string elements beyond that point. We assume that the reason Sussman and Westbury apparently observed a string-element effect is that they compared a one-consonant sequence with a three-consonant sequence.

There is still a good deal that remains unclear about both models and data. We agree that the onset of rounding is clearly influenced by peripheral biomechanical concerns; thus in the Sussman and Westbury data, rounding for /u/ begins at a different time following /i/ and /a/, and in our data, at a different time for /u/ following /u/ and /i/. However, by examining a set of utterances whose consonant durations for each subject were fairly well distributed through a wide range of durations, we believe we have shown the rounding gesture to be linked to the vowel articulation. That is, the specification of lip position for the consonants is not altered by a migrating vowel feature. Instead, and as we have also suggested elsewhere (Bell-Berti and Harris, in press), we see the vowel-rounding gesture beginning at a relatively fixed time before the acoustic onset of the vowel and simply co-occurring with some portion of the preceding lingual consonant articulations.

ACKNOWLEDGMENTS

This work was supported by NINCDS grants NS-13617 and NS-05332 and BRS grant RR-05596 to the Haskins Laboratories.

[1]Optimum choice of timing measures from EMG signals depends on several considerations, including both the nature of the EMG data themselves and the use for which the measurements are intended. There are three sources of token-to-token variability in EMG signals whose relative magnitudes bear on the choice: uncorrelated electrical noise, the statistical nature of motor-unit excitation, and articulatory timing variation. Effects of this third source are minimized by control of speaking rate and by judicious choice (and careful measurement) of the acoustic reference point. When the first two sources of variability are large—and especially when the EMG onsets are gradual—measurement from the average signal is preferred. Since we frequently encounter both gradual onsets and relatively noisy signals, use of the ensemble average in determining EMG onset time is generally the method of choice (Baer *et al.*, 1979).

[2]This value was chosen because it assured that we were not identifying random background noise as the beginning of activity. This 5% point was exceeded for each speaker for the utterance "loo tool," which had a relatively short consonant string and, consequently, the minimum level of EMG activity between the two rounded vowels did not fall to 5% of the peak activity. For these cases, we chose the times at which minimum activity occurred.

Allen, G. D., Lubker, J. F., and Harrison, G. (1972). "New paint-on electrodes for surface electromyography," J. Acoust. Soc. Am. 52, 124.

Baer, T., Bell-Berti, F., and Tuller, B. (1979). "On determining EMG onset time," in *Speech Communication Papers Presented at the 97th Meeting of the Acoustical Society of America*, edited by J. J. Wolf and D. H. Klatt (Acoustical Society of America, New York).

Bell-Berti, F. (1980). "Velopharyngeal function: A spatial-temporal model," in *Speech and Language: Advances in Basic Research and Practice*, Vol. 4, edited by N. J. Lass (Academic, New York).

Bell-Berti, F., and Harris, K. S. (1974). "More on the motor organization of speech gestures," Haskins Labs. Status Rep. Speech Res. SR-37/38, 73–77.

Bell-Berti, F., and Harris, K. S. (1979). "Anticipatory coarticulation: some implications from a study of lip rounding," J. Acoust. Soc. Am. 65, 1268–1270.

Bell-Berti, F., and Harris, K. S. (in press). "A temporal model of speech production," Phonetica.

Benguerel, A.-P., and Cowan, H. A. (1974). "Coarticulation of upper lip protrusion in French," Phonetica 30, 41–55.

Bronstein, A. J. (1960). *Pronunciation of American English* (Appleton-Century-Crofts, New York).

Daniloff, R. G., and Moll, K. L. (1968). "Coarticulation of lip rounding," J. Speech Hear. Res. 11, 707–721.

Engstrand, O. (1980). "Acoustic constraints or invariant input representation? An experimental study of selected articulatory movements and targets," Rep. Uppsala Univ. Dep. Linguist. 7, 67–95.

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

Fromkin, V. A. (1966). "Neuromuscular specification of linguistic units," Lang. Speech 9, 170–199.

Gay, T. J. (1978). "Articulatory units: segments or syllables?," in *Syllables and Segments*, edited by A. Bell and J. B. Hooper (North-Holland, Amsterdam).

Harris, K. S., Lysaught, G. F., and Schvey, M. M. (1965). "Some aspects of the production of oral and nasal labial stops," Lang. Speech. 8, 135–147.

Henke, W. L. (1966). "Dynamic articulatory model of speech production using computer simulation," unpublished doctoral dissertation (MIT, Cambridge, MA).

Kewley-Port, D. (1973). "Computer processing of EMG signals at Haskins Laboratories," Haskins Labs. Status Rep. Speech Res. SR-33, 173–183.

Lehiste, I. (1960). "An acoustic-phonetic study of internal open juncture," Phonetica 5 (Suppl.), 1–54.

MacNeilage, P. F. (1970). "Motor control of the serial ordering of speech," Psychol. Rev. 77, 182–196.

McClean, M. (1973). "Forward coarticulation of velar movement at marked junctural boundaries," J. Speech Hear. Res. 16, 286–296.

Sussman, H. M., and Westbury, J. R. (1981). "The effects of antagonistic gestures on temporal and amplitude parameters of anticipatory labial coarticulation," J. Speech Hear. Res. 22, 16–24.

Tatham, M. A. A., and Morton, K. (1968). "Some electromyography data towards a model of speech production," Univ. Essex Lang. Cent. Occas. Pap. 1, 1–59.