ON THE NOTION "STRENGTH" OF COARTICULATION

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It has been suggested elsewhere (Bladon and Al-Bamerni 1976) that the numerous factors which constrain the domain and the direction of coarticulatory effects in speech can best be described by postulating the notion of "coarticulation resistance" (CR) as the relevant principle of articulatory control. The speech production mechanism is hypothesized to have continuous access to CR information, which can be considered to be initially stored linguistically as a scalar feature specification [n CR] attaching to each extrinsic allophone and boundary condition. Thus it has been demonstrated, for example, that British (RP) English dark syllabic [ɫ̩] is highly resistant to coarticulation, while clear nonsyllabic [l] is much more susceptible, and we propose initially to provide those allophones with specifications such as [5 CR] and [2 CR], respectively. The numerical value of the CR index is re-computed at a level of articulatory planning by what might be termed a CR compiler to take account of a wide range of constraints imposed by motor compatibility, by the structure of the phonetic system, etc. It is further suggested that coarticulation may proceed freely in either direction (left-to-right or right-to-left) in time, until impeded by a specification of CR on some segment.

One advantage of this formulation is that it enables us to refine our ideas about the degree of coarticulation a segment shows, and to quantify the terms "weak coarticulation" and

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"strong coarticulation" which tend to be used informally (e.g. "segment [A] is weakly coarticulated with the following segment [N] in respect of feature F"). Two kinds of condition can produce a "weak" realization of F on [A]. Firstly, if [A] has a moderately high specification of CR, and provided F is itself reasonably "strong", coarticulation on [A] will not be impeded altogether, but "weakened". [A] can be said to show weak coarticulation, and this can be expressed in appropriate numerical terms.

Secondly, consider a case where the feature F, spreading into [A], is itself realized only "weakly" on [N] in the first place. According to the observed coarticulation behaviour, two different hypotheses can be entertained. On the one hand, it is possible that a moderate CR index on [A] will nevertheless be sufficient to inhibit coarticulation onto [A] of the now "weak" feature F: in that event the CR compiler must be provided with a means of detecting the "strength" ("weakness") of the original specification of the feature available for coarticulation. On the other hand, it is alternatively possible that [A] may show evidence of coarticulation even with a "weak" feature. In that case, the term "weakly coarticulated" would seem inappropriate (i.e. [A] is weakly nasalized, weakly labialized etc., but not weakly coarticulated), and this would provide evidence that the operation of the CR compiler need not be sensitive to the "strength" of the coarticulated feature.

The present experiment was designed primarily to obtain evidence relating to this question of the possible coarticulation of a weakly specified feature. RP English /r/ provides a test case, being frequently produced with slight labialization, in particular with slight protrusion and rounding of both lips, or sometimes of mainly the lower lip (Ladefoged 1971: 62; Jones 1972: 195). A speech sample was devised containing consonant strings of varying length preceding /r/. Interest centred on how far left into the preceding consonant string (if at all) there would be anticipatory coarticulation of the labialization of /r/.

It is known from other studies (Daniloff and Moll 1968, Gay 1977) that the labialization accompanying /u/, which can be shown (see below) to be an example of a "stronger" articulatory gesture than that accompanying /r/, is coarticulatorily advanced leftwards across all consonants within the CV ("articulatory syllable") unit. Gay found, for example, in sequences of English nonsense strings of the type /utu, ustu, ukstu/, that two separate peaks of electromyographic activity were registered from the orbicularis oris muscle, each peak corresponding to a labialization gesture for an /u/, but that the second peak occurred as early as possible in the consonant string. The behaviour of /r/ in this regard was investigated as follows.

Electromyographic (EMG) activity from the orbicularis oris muscle of two young adult speakers of RP was measured by surface electrodes. One speaker was recorded at the Institute of Phonetics, University of Copenhagen, using solid rectangular disc electrodes made of silver and secured to the upper and lower lips by tape. This speaker was the same person who served as subject for the experiment by Gay (1977). The other speaker was recorded at the Department of Phonetics, Stockholm University, using electrodes of the "paint-on" type, made of a mixture of cement, acetone and fine silver powder (for more details of this method see for instance Allen and Lubker 1972). On both occasions the electrode sites were on the vermilion border of the upper and lower lips just to the subject's right of midline. Mingograph tracings were obtained of the audio signal (duplex oscillogram and intensity curve), of a raw EMG signal from each of the two lips, and of a rectified and integrated ($\underline{t}$ = 20 ms) EMG signal from each lip.

Some sample EMG curves are reproduced as Fig. 1. The recording in the upper part of the figure was made in Copenhagen, that in the lower part in Stockholm (different speakers). All

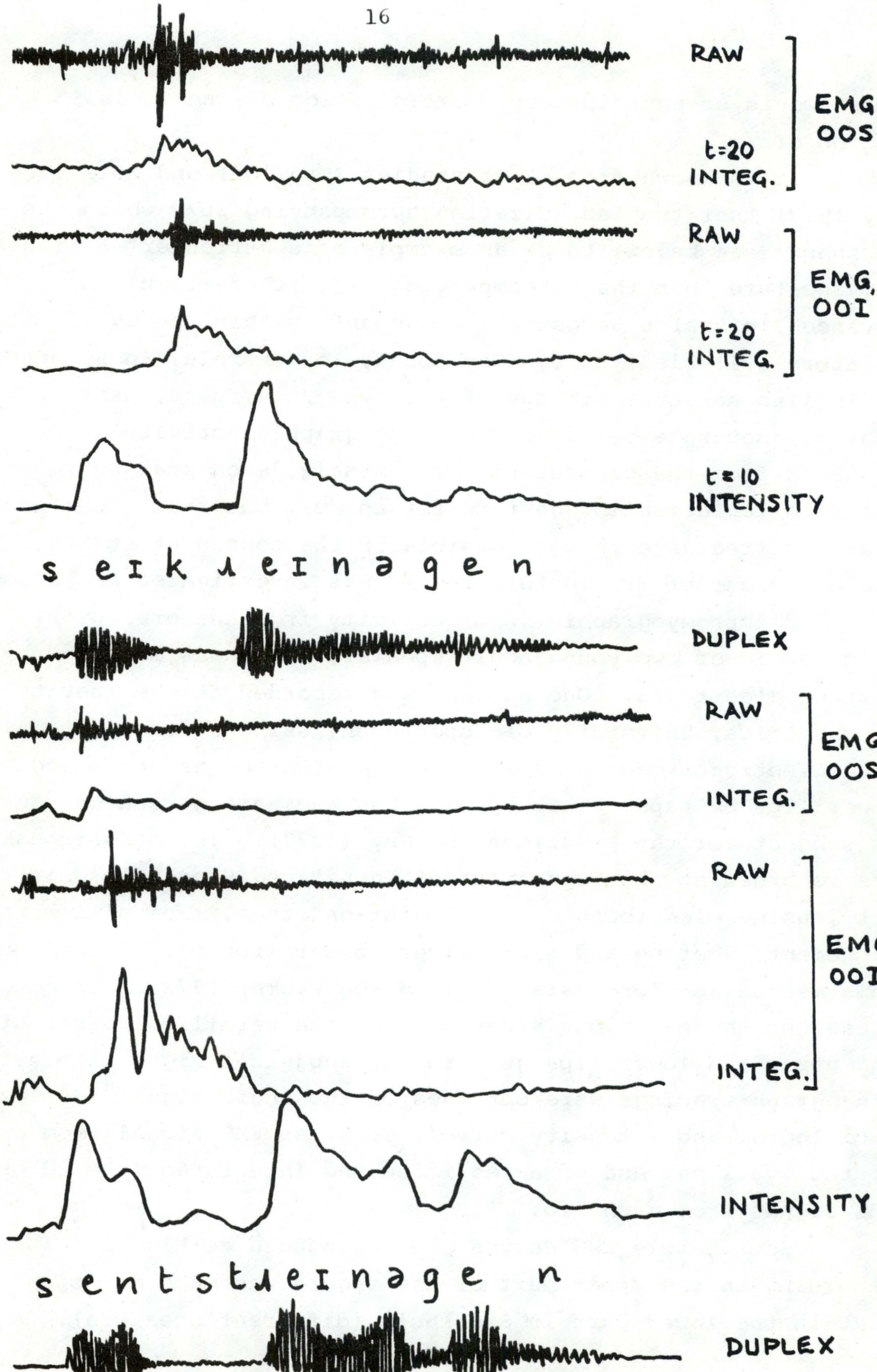


Figure 1

Sample EMG curves of orbicularis oris superior (OOS) and orbicularis oris inferior (OOI), and intensity curves and duplex oscillogram of the audio signal. For further explanation, see text.

the EMG curves were highpass filtered at 100 Hz; the linear intensity curves were highpass filtered at 500 Hz; and integration times of 20 and 10 ms were used for the EMG and intensity curves, respectively.

The speech sample consisted of each of the words listed in Table 1, Columns 2 and 3, embedded into each of the frames shown in Table 1, Column 1, and spoken with a falling intonation nucleus on the word from Column 2 or 3. This corpus was read twice by each of the two speakers, with the intention that the two readings would provide an indication of the variability of data collected by this method (see Appendix for discussion). The purpose of including the items in Column 3 was to obtain control information on the relative "strength" of labialization in /r/ in comparison with other labial or labialized sounds.

Table 1

Items in the speech sample.

1.		2.	3.
Say ... again	(a) /r/	red	bed
See ... again		rat	wed
Set ... again		rain	fed
Sent ... again	(b) /Cr/	train	shed
Do ... again		drain	red
Saw ... again		crane	
Shoot ... again		grain	
	(c) /CCr/	in train	
		engrain	
	(d) /CCr/	strain	
		screen	
	(e) /CCCr/	in strain	
		on screen	
	(f) /CCCCr/	old screen	
		old strip	

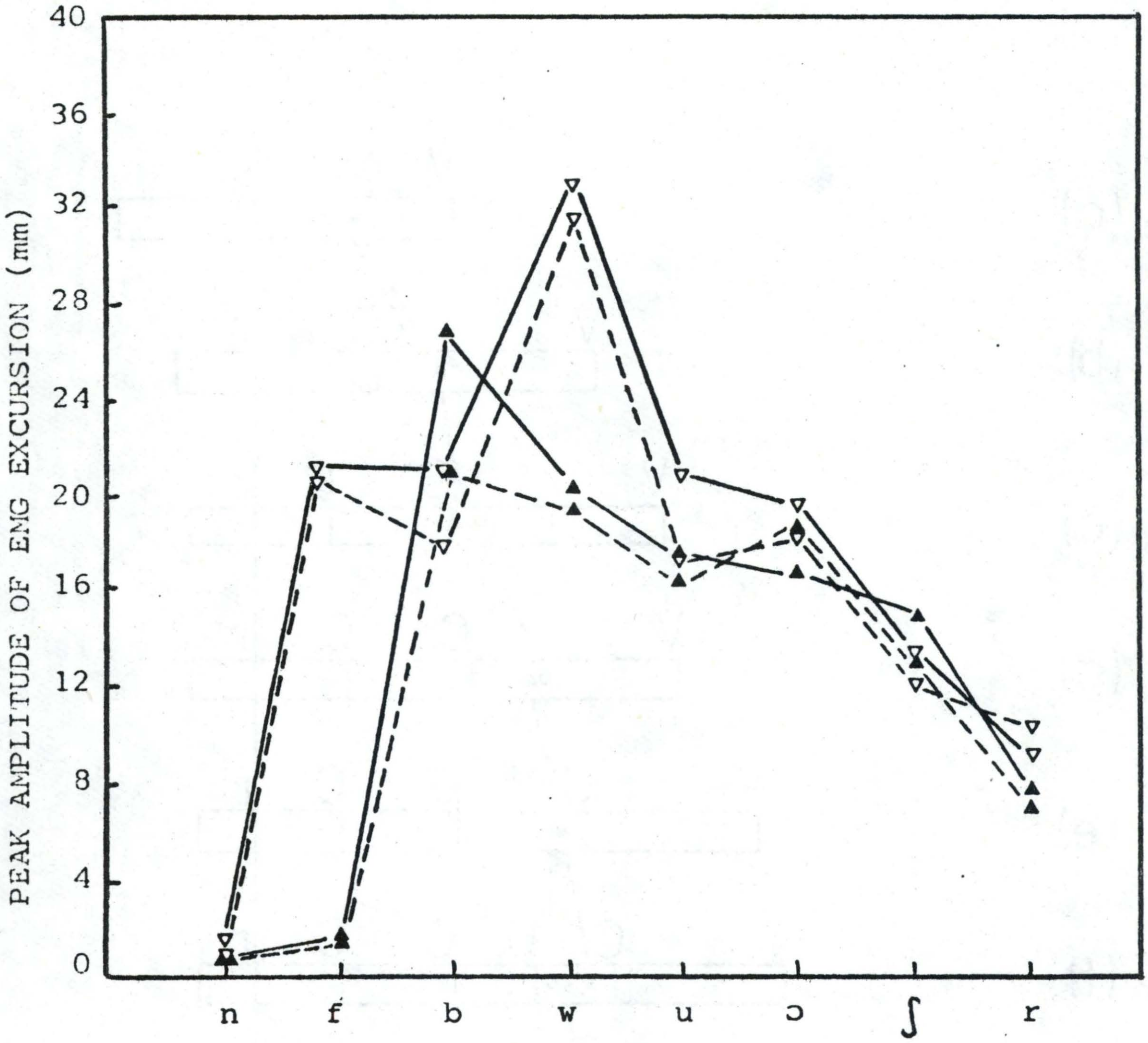
The first results to be considered will be those relating to that control group of data in Table 1, Column 3. Fig. 2 shows the peak amplitude of excursion of the rectified and integrated EMG trace, for each of several labial or labialized sounds. Each data point represents the mean value of 14 tokens. From this display of the peak innervation of orbicularis oris, it can be confirmed that labial activity is strongest in those consonants with primary labial approximation /b w f/ and in the rounded vowels /u ɔ/, and weakest in the sounds /ʃ r/ which are traditionally said to have secondary articulation at the lips.

Turning now to the principal results, Fig. 3 summarizes the observed timing relationships between the speech sound segmented from the audio traces and the firing instant for orbicularis oris in both lips. The onsets of /r/ are aligned. These are the findings of interest:

(1) In sentences of the type "Say rain again" (Fig. 3(a)), the firing instant of the orbicularis oris muscle (defined by a steep excursion on the integrated EMG curves) precedes by some 60 to 70 ms the acoustic evidence of the /r/ onset as determined from the audio signal (by a sharply reduced intensity curve and a reduction in the oscillogram amplitude).

This acoustic lag accords well with other investigators' findings for this muscle, and with the time scale cited by Catford (1977: 6) for neuromuscular, organic and aerodynamic phases.

(2) The firing instant for orbicularis oris in /r/ advances progressively through the sequence of environments (a) C_0r to (f) C_4r. That is, right-to-left coarticulated labialization takes place across a sequence of any number of alveolar consonants; but is arrested by a left V boundary. This provides further evidence for the postulation of the "articulatory syllable" (of the form CV, where C is any number of consonants) at whose boundaries coarticulation resistance



<u>Figure 2</u>

"Strength" of labial activity for various sounds.
Filled triangle (▲): upper lip.
Unfilled triangle (▽): lower lip.
Two speakers represented by —— and ----

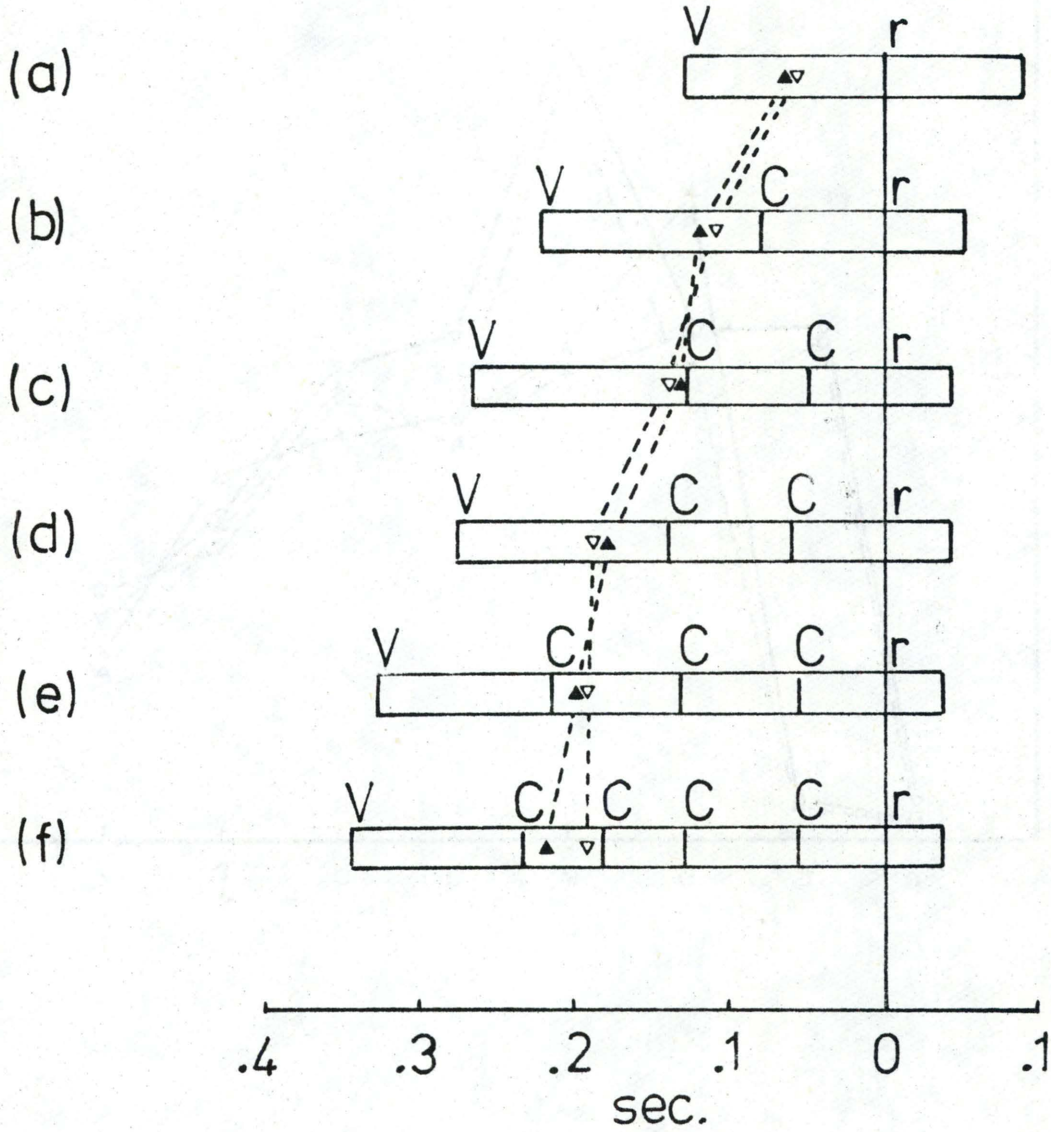


Figure 3

Firing instant of orbicularis oris muscle anticipating /r/, in various environments (a) to (f)-see Table 1 for details.
Filled triangle (▲): upper lip firing instant.
Unfilled triangle (▽): lower lip firing instant.

is high (Kozhevnikov and Chistovich 1965; Bladon and Al-Bamerni 1976).

(3) Following on from finding (2), it is to be noted that coarticulation proceeds in particular unimpeded by an intervening /s/ in the string. This argues against the possibility that English /s/ might have a high overall specification for CR under all conditions; a view speculated upon in Bladon and Nolan (1977) on the evidence of, firstly, the resistance they found in /s, z/ to coarticulatory shifts of laminality towards apicality, and secondly, following Amerman et al. (1970), the inhibition offered by /s/ to coarticulated jaw-opening anticipating English /æ/. Rather, the CR compiler must be sensitive to the 'feature' being coarticulated, allowing /s/ to labialize freely, but not to shift its point of stricture or jaw-opening.

(4) The right-to-left coarticulation takes place over a consonant string irrespective of intervening morpheme boundaries in sentences like "Set train ...", "Sent train ...", "Set strain ...", "Sent strain ...". This is in accordance with similar findings by Daniloff and Moll (1968: 714) and others. But in those cases where a morpheme boundary occurs in Fig. 3, namely (c), (e) and (f), there is some suggestion that coarticulation begins slightly later, in or near to the first C.

The evidence of (2), (3) and (4) above indicates that the "weak" labialization accompanying English /r/ is coarticulated anticipatorily over no smaller a domain of segments than was the "stronger" labialization accompanying /u/. It is probably the case that a given specification to coarticulated labialization anticipating /u/, would at the same time never be so high that it would prevent coarticulation with /r/. More generally, it may then not be necessary to build into the CR compiler, in a model of speech production control, a mechanism for assessing the articulatory "strength" of the coarticulated feature.

The CR compiler will, however, have to be constrained by numerous disparate articulatory and linguistic properties, and while it seems from the above experiment that it may not be necessary to include among them a sensitivity to feature-"strength" in an articulatory sense, it may be worthwhile summarizing here those properties known from other work to be relevant:

(a) "universal" marking conventions - which, for example, will assign a universally high CR index to the intonation-group boundary;
(b) language-specific properties - such as the fact cited by Ladefoged (1967: 62-4) that while French and English both show a /k/ coarticulatorily advanced before an /i/ vowel, only French shows the similar effect after /i/;
(c) dialect-specific properties - British English shows less anticipatory nasalization of a vowel before a nasal than does American English;
(d) speaker-specific properties - according to Su, Li and Fu (1974), coarticulated vowel-quality in a nasal may well be speaker-identifying;
(e) properties of the phonetic system - Irish (with three laterals in its system) shows much less coarticulated vowel-quality in a lateral than does British Englih (with two) which in turn shows less than American English (with one);
(f) properties of phonological structure - CV ("articulatory syllable") boundaries, as mentioned, seem to have high CR;
(g) properties of motor constraints - jaw-opening is incompatible with /s/ probably because it excessively deforms the friction passage;
(h) properties of the coarticulated feature - English /s/ will allow coarticulation of lip-rounding (as seen above) but not of shift in lower articulator;
(i) idiosyncratic CR specifications for individual segments - such as the high CR of RP [ɫ].

It is safe to assume that the above list is not yet complete. However, it is perhaps a small consolation that, apparently, instances of "weak" versus "strong" coarticulation do not yet justify in themselves further extension of this apparatus.

Acknowledgement

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Appendix

Some impression of the consistency observed in the EMG curves can be obtained from Table 2. This shows, separately for the two muscles orbicularis oris superior and inferior, and separately for each speaker A and B, the duration of coarticulated labialization measured between the EMG firing instant and the acoustic onset of /r/. From these results it can be seen that rather consistently speaker A's values exceed those of B to a small extent (approximately by 8%). Table 2 also shows the mean of the two speakers' data (shown as $\bar{x}$ and used as the basis for Figure 3), the standard deviation, and the results of a t-test performed to compare the data of the first reading with that of the second. The importance of this comparison lies in the widely observed tendency for EMG signals to show appreciable occasion-to-occasion variation. From the t-values it can be stated that in all cases there is no significant difference between the readings ($p > 0.05$). It should also be noted that our results can be compared fairly directly with those of Gay (1977) for the vowel /u/, since Gay's speaker was the same person as one of our subjects.

Table 2

Firing instant in orbicularis oris superior (OOS) and inferior (OOI) anticipating RP /r/. For explanation, see text in Appendix.

		OOS				OOI				
		spkr A spkr B	$\bar{x}$	s	t	spkr A spkr B	$\bar{x}$	s	t	n
(a)	/r/	65 67	66	12.8	0.76	66 56	61	17.5	0.55	48
(b)	/Cr/	123 105	114	20.3	0.44	118 98	108	25.2	0.49	64
(c)	/nCr/	150 130	140	17.0	0.97	145 141	143	16.6	0.33	32
(d)	/sCr/	197 173	185	30.7	0.29	191 185	188	27.3	0.62	32
(e)	/CCCr/	201 183	192	41.3	0.70	205 187	196	47.1	0.76	32
(f)	/CCCCr/	231 203	217	32.8	1.06	180 199	189	36.0	0.90	32

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