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Journal of Phonetics (1992) **20**, 111–126

Gestural aggregation in speech: laryngeal gestures

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Received 29th January 1990, and in revised form 30th October 1990

It is well known that the units of speech are not produced strictly sequentially but overlap with each other; this phenomenon has been referred to as coarticulation, coproduction, or blending. The present experiment examines one intra-articulator example of temporal overlap, namely the combination of successive opening and closing gestures in the larynx. Two subjects produced the utterance *Kiss Ted* at several different speaking rates with stress on the first or second word. Laryngeal abduction–adduction was monitored using transillumination and fiberoptic video recording. Results show that at slow rates two separate glottal openings occur associated with the fricative and the stop, respectively. At fast rates, a single smooth glottal opening movement is seen. At intermediate rates, partially overlapping gestures are found. These findings suggest that two underlying gestures are being blended into a single composite movement. Simulations suggest that the combination process may be some type of summation.

1. Introduction

The units of speech are not produced strictly sequentially but rather overlap with each other. This phenomenon has been referred to as coarticulation, coproduction or blending, and there is an extensive body of literature describing its articulatory, acoustic and perceptual aspects (e.g., Stevens & House, 1963; Kozhevnikov & Chistovich, 1965; Stevens, House & Paul, 1966, Öhman, 1966; Daniloff & Moll, 1968; McNeilage & DeClerk, 1969; Benguerel & Cowan, 1974; Bell-Berti & Harris, 1979, 1982; Sussman & Westbury, 1981; Lubker, 1981; Lubker & Gay, 1982; Perkell, 1986). For example, a voiceless fricative /s/ preceding a rounded vowel is normally produced with lip-rounding; however, for many speakers when the fricative occurs before an unrounded vowel, no lip-rounding is found. In both of these cases the lip conditions for the vowel overlap with the fricative production. As a consequence of this overlap, the vocal tract shape represents an aggregate of gestures associated with the different production units (cf. Fant, 1962).

While there are theoretical frameworks in the study of speech (e.g., Lindblom, 1963; Öhman, 1967; Fowler, 1980; Saltzman & Munhall, 1989) and in the study of

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other movements (e.g., Flash, 1990; Morasso, 1986; Milner & Ijaz, 1990) that can accommodate overlap of movements, much is unknown about the motoric implementation of two or more simultaneous activations of the articulators. If two speech production units simultaneously are vying for an articulator this must be meted out at the muscle and articulator level in a manner that maintains fluency and maintains communicative intent. In this paper we focus on how this overlap of movements is implemented by the vocal tract within a single articulator. This is an important condition for the study of coarticulation since incompatible movements have frequently been viewed as a constraint on the extent of coarticulation (e.g., Henke, 1966). For example, in many views anticipatory lip rounding can extend only over segments that are not specified negatively for rounding.

The present experiment was designed to investigate the combination of successive opening and closing gestures in the larynx. A situation similar to the one investigated here has been reported by Löfqvist & Yoshioka (1981). They investigated laryngeal activity in the production of voiceless obstruents in Icelandic. In particular, they noted that for a cluster of two successive voiceless consonants, two independent laryngeal abduction–adduction gestures occurred, one for each consonant. However, as speaking rate increased, the two gestures seemed to slide on top of each other and the resulting movement could be taken as a blend of two underlying gestures (see Löfqvist & Yoshioka, 1981, Figs 4 and 5).

One possible explanation for the Löfqvist & Yoshioka finding is that the effects of different underlying movements at the larynx could be combined by a simple algebraic process. Recently, such an explanation has been proposed for the irregularities in the velocity profiles of simple aiming movements with the arm (Milner & Ijaz, 1990). Precise aiming movements have frequently been shown to be composed of a number of submovements (e.g., Woodworth, 1899). Usually, this means a large initial movement and then some smaller corrective movements. Milner & Ijaz (1990) have suggested that the irregularities in the tangential velocity of aiming movements can be accounted for if submovements are linearly superimposed to create a single composite movement.

In the present experiment we explore this possibility for speech and extend the Löfqvist & Yoshioka (1981) finding to native speakers of English. Some material presented here has appeared in a preliminary form in Munhall & Löfqvist (1987).

2. Method

2.1. *Subjects*

The subjects were two native speakers of English, one female (RSS) and one male (KM, the first author).

2.2. *Stimuli*

The subjects produced the utterances *Kiss Ted* at several self-selected speaking rates. Within a single sequence, stress occurred on either the verb or the noun. The aim of both the rate and stress manipulations was to elicit segment durations spanning as large a range as possible. Thus, stress was not investigated in itself but it served to introduce another source of temporal variation. In the experiment, subjects began speaking at a self-chosen "slow" rate producing five repetitions of each utterance. They were then instructed to increase the speaking rate in small increments until their fastest rate was achieved. This procedure was repeated, beginning again at the slow speaking rate. Hence, no attempt was made to control the number of rates for each subject or for each rate scaling sequence. For subject RSS, 124 *Kiss Ted* sequences were analyzed, and for subject KM, 144 sequences were analyzed.

2.3. *Equipment*

Recordings of laryngeal abduction and adduction during voiceless consonant production were made using transillumination and fiberoptic video recording. Comparisons between transillumination and fiberoptic films (Löfqvist & Yoshioka, 1980) and also between transillumination and high-speed films (Baer, Löfqvist & McGarr, 1983) have shown good agreement. Since the transillumination signal is uncalibrated, comparisons should be confined to records obtained during a single experimental session. A fiberscope provided illumination of the larynx, and the light passing through the glottis was sensed by a phototransistor placed medially on the neck at the level of the cricothyroid membrane. The transillumination signal was recorded on FM tape. A microphone signal was recorded simultaneously in direct mode. A video recording was also made of the fiberoptic image.

2.4. *Analysis*

Measurements were made interactively on a computer and comprised a number of temporal intervals. Sample records are presented in Fig. 1, showing two tokens of *Kiss 'Ted* produced at a slow and fast speaking rate, respectively. As an index of speaking rate, we used the interval from the offset of the vowel in *Kiss* to the onset of the vowel in *Ted.* We view this interval as a good overall index of speaking rate, taking into account interword timing as well as segmental timing variation.

As a measure of intra-articulator timing, we used the interval between the two peaks of glottal opening [Fig. 1(a)]. If a single opening movement occurred, as in Fig. 1(b), the interval from peak opening to peak opening was zero. In order to decide whether one or two opening movements were made, we used the first derivative of the position signal (i.e., the velocity). The criterion used was based on changes in the sign of the first derivative. In a single movement the velocity normally changes once from positive during opening to negative during closing. If an additional sign change was observed, the utterance was classified as having two peaks. Analyses using the second derivative of position (acceleration) yielded similar results. Peak openings were identified as zero crossings in the velocity record. In the rare case of a plateau of zero velocity values, the mid-point of the plateau was designated as the peak.

An interarticulator temporal measurement consisted of the position of the peak opening(s) in relation to frication onset for the /s/.

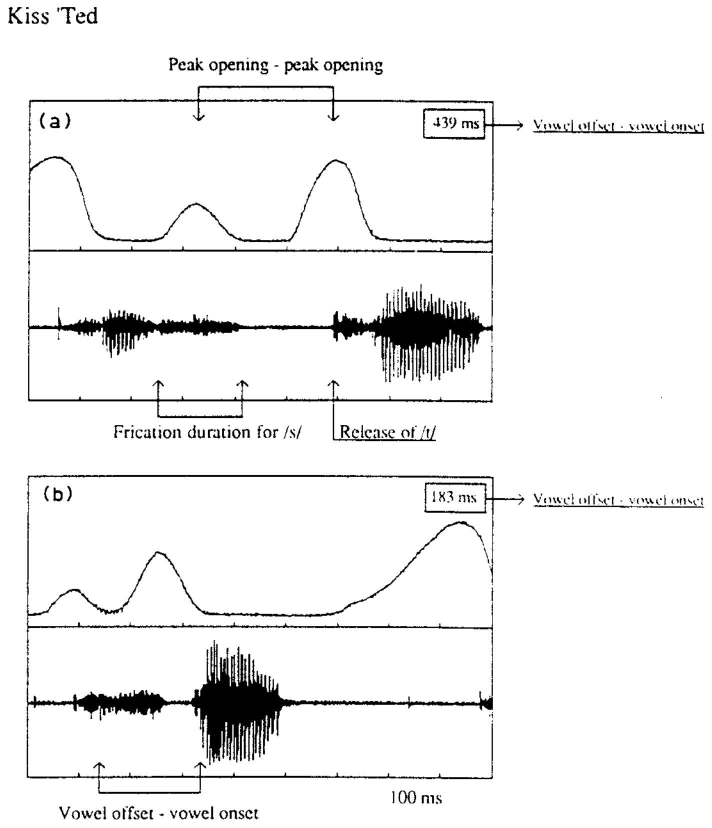

Figure 1. Productions of *Kiss 'Ted* with (a) two laryngeal gestures and (b) a single laryngeal gesture for /s/ and /t/. Selected articulatory events and intervals are indicated.

3. Results

3.1. *Temporal measurements*

We shall first present the results of the temporal measurements and later address the shape of the laryngeal movements. The purpose of the experiment required the sampling of as broad a range of speaking rates as possible since that would allow us to observe many different types of laryngeal coordinations. The ranges of variation in the interval between vowel offset and vowel onset for the two subjects can be seen in the x-axis values in Figs 2 and 3. This interval serves as an index of speaking rate. Obviously, the productions of subject RSS spanned a larger range than those of subject KM. At the same time, the majority of the measured intervals fall within the same range for the two subjects. Note, also that the very long intervals for subject RSS in these figures form a distinct group that is well separated from the other measurements.

In the laryngeal kinematic data for KM and RSS one or two laryngeal movements were observed depending on the particular trial. The majority of the productions contained only one glottal movement; two movements occurred in 18.75% of KM's

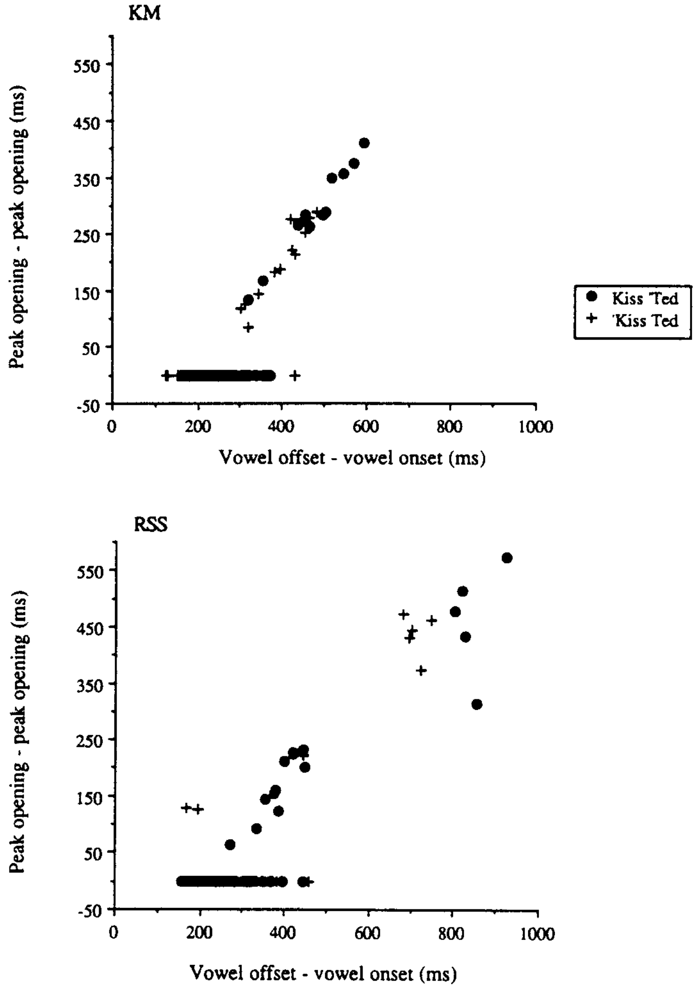

Figure 2. Plot of the interval from peak glottal opening to peak glottal opening as a function of the interval from vowel offset to vowel onset for the utterance *Kiss Ted*.

productions and in 19.35% of RSS's productions. The duration of the interval between successive peak glottal openings is plotted as a function of speaking rate in Fig. 2; zero duration for this interval indicates that only one opening movement occurred. It is evident that the peak to peak distance decreases with rate for both subjects. At fast rates only one movement is found. The transition from two laryngeal movements to one is well-defined for subject KM. In this case, there is only a small region of overlap between productions with one and two movements. For subject RSS, however, this region of change is less clearly defined. Productions with one and two movements are both found at the very fast rates. However, in the slower rates of both subjects only two movement-productions are observed. Stress position had no obvious effect on the patterns observed in this figure.

Figure 3 therefore, differentiates one-movement from two-movement patterns, but not the stress position. It plots position of peak glottal opening relative to the

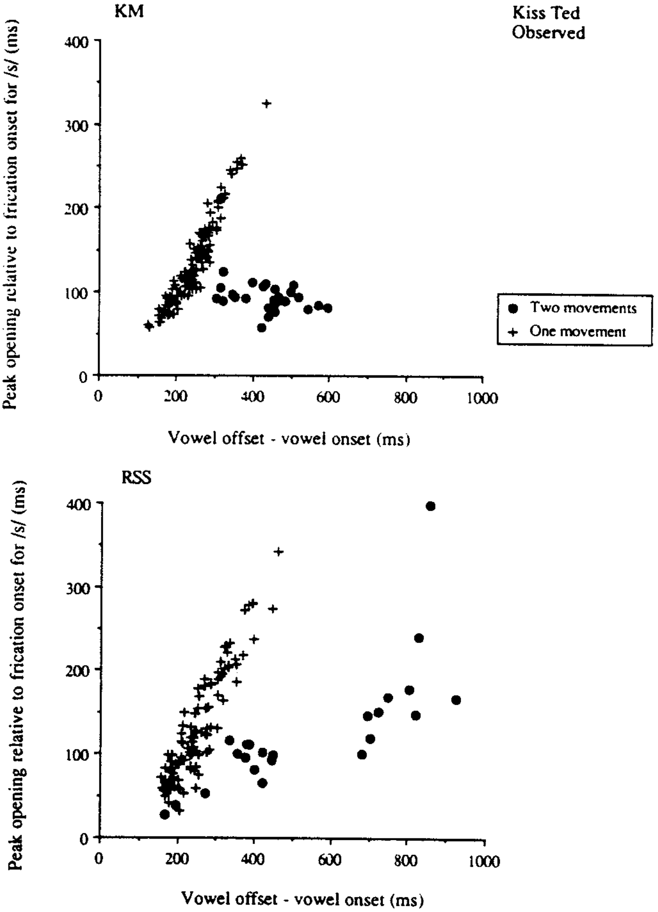

Figure 3. Plot of the position of peak glottal opening relative to the onset of frication for the /s/ in *Kiss* as a function of the interval from vowel offset to vowel onset.

onset of frication for the /s/ in *Kiss* again as a function of speaking rate. For the two-movement trials, the first laryngeal movement is the peak glottal opening used for this analysis. It is evident from Fig. 3 that the productions with one and two glottal movements form two separate groups. When a separate movement is made for the /s/ in *Kiss*, peak opening of the movement is located at almost the same place in relation to frication onset for subject KM. For subject RSS, on the other hand, peak glottal opening to frication onset does increase somewhat with longer intervowel intervals. However, when only one glottal movement is made, its relationship to onset of frication is quite different. For both subjects, the interval from peak opening to frication onset shows a strong positive relationship to the intervowel interval. Note, that when one and two movement productions have a similar intervowel duration, in the range 300–400 ms, the location of peak glottal opening relative to frication onset is quite different. The occurrence of a single movement increases the peak to frication onset interval by 100–150 ms. The relationships shown in Fig. 3 are linear, in part, because of the part–whole nature of the two variables. The point of this plot, however, is simply to contrast the relative timing of the one and two movement patterns, not to raise the question of the strength of the linear association of the two variables. Thus, no attempt was made to decompose the regression into part–whole and "true" regression components (see Munhall, 1985; Benoit, 1986).

To sum up the results for timing, speaking rate affects the duration of the segments. As the speaking rate increases, the duration of the interval between the two glottal openings for /s/ and /t/ decreases to eventually become zero, indicating that only a single laryngeal movement is made for the entire /s + t/ cluster. The relative timing of the laryngeal and oral articulations for the /s/ differs between the productions with one and two glottal movements.

3.2. *The shape of the movements*

We have seen that the interarticulator phasing differs for productions with one and two laryngeal articulatory movements. What about the shape of the laryngeal movements? Figure 4 presents several tokens of *Kiss 'Ted* produced at different rates for the two subjects. These productions have been arranged in increasing duration of the interval between vowel offset for /ɪ/ in *Kiss* and vowel onset for /ɛ/ in *Ted*; the duration of this interval is given, in milliseconds, in the upper right-hand corner of each panel. The selection was made so as to cover the range of speaking rates shown in Fig. 2.

Generally, we see the following pattern. At fast rates, a single movement is found with similar durations of the abduction and the adduction phases. At slow rates, two separate movements occur; between the two movements, the glottis is generally closed. At the intermediate rates, one opening movement is found. This movement does, however, show traces of the two individual gestures. That is, the movement is not symmetrical but rather shows some extra "adjustments". Note, in all the displayed records with two movements the laryngeal movement corresponding to the /t/ is larger than the movement corresponding to the /s/. In the data shown in Fig. 4, all the utterances had the stress on the noun, *Ted*; however, the same pattern is found when the stress occurred on the verb, *Kiss*. This difference in amplitude presumably reflects differential effects of stress on the onset and coda since /s/ movements have been shown to be larger than /t/ movements when stress and syllable position are matched (Yoshioka, Löfqvist & Hirose, 1981; Munhall & Ostry, 1985).

One method of accounting for the "adjustments" observed in utterances produced at intermediate rates would be to assume that the two original laryngeal movements were being combined to produce a single composite movement. To simulate this process we have taken two laryngeal movements for subject KM and added them at various degrees of overlap. The two gestures chosen were smoothed versions of the movements for /s/ and /t/ shown in the top of Fig. 1. The assumptions in the simulation were as follows: (1) The two underlying gestures' time courses were unaltered by the overlap. (2) The second gesture's onset is unconstrained; that is, it can begin at any phase of the first gesture. (3) The observed movement is the vector sum of the two underlying patterns for each degree of overlap. The results of these summations are shown in Fig. 5. Note that the overall shape changes in these simulated curves closely approximate the observed patterns for KM shown in Fig. 4.

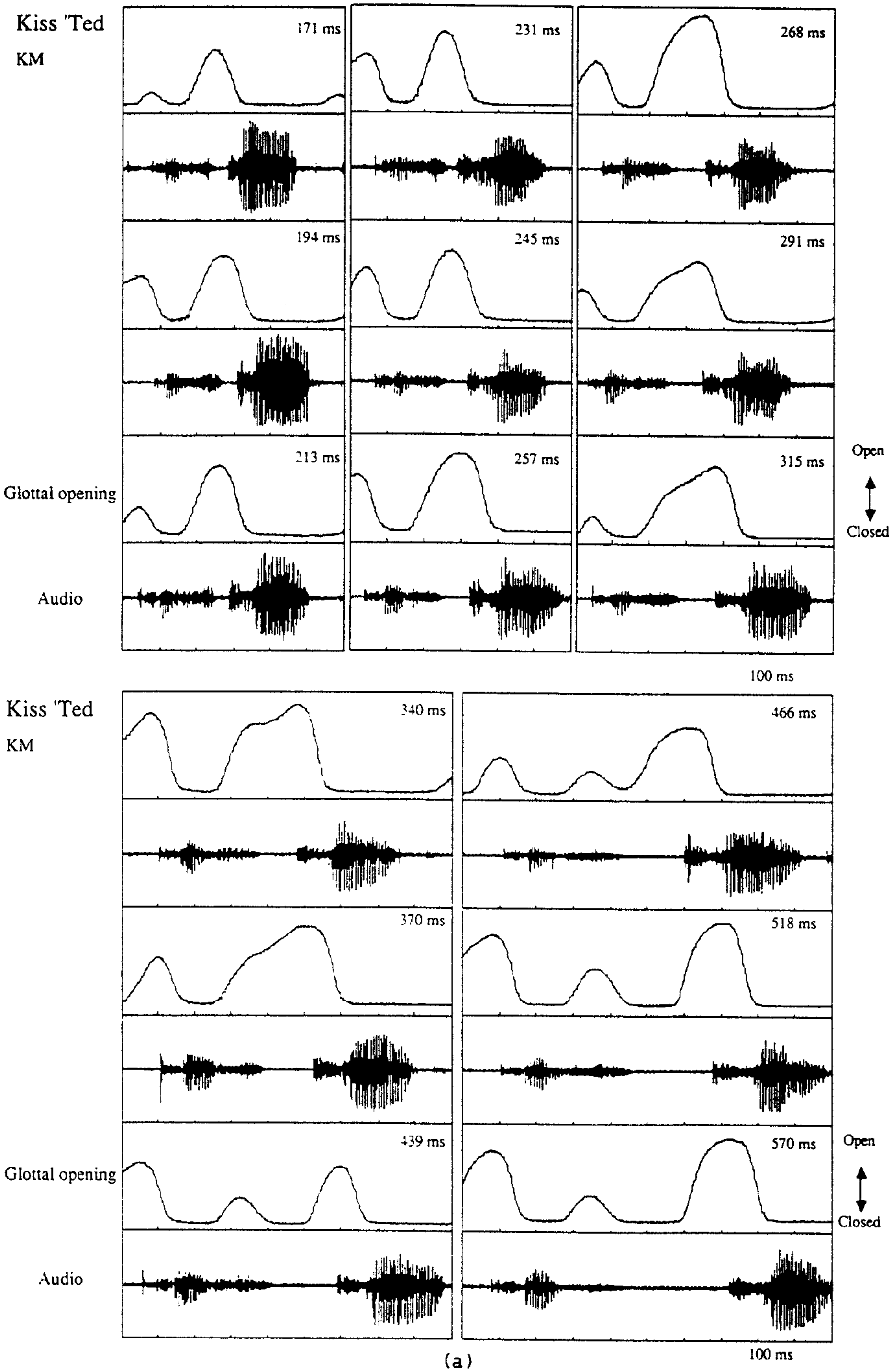

Figure 4. Productions of *Kiss 'Ted* by (a) subject KM and (b) subject RSS arranged in order of decreasing speaking rate. The number in the upper right corner of each panel is the interval from offset to onset of the vowels preceding and following the consonant cluster, respectively.

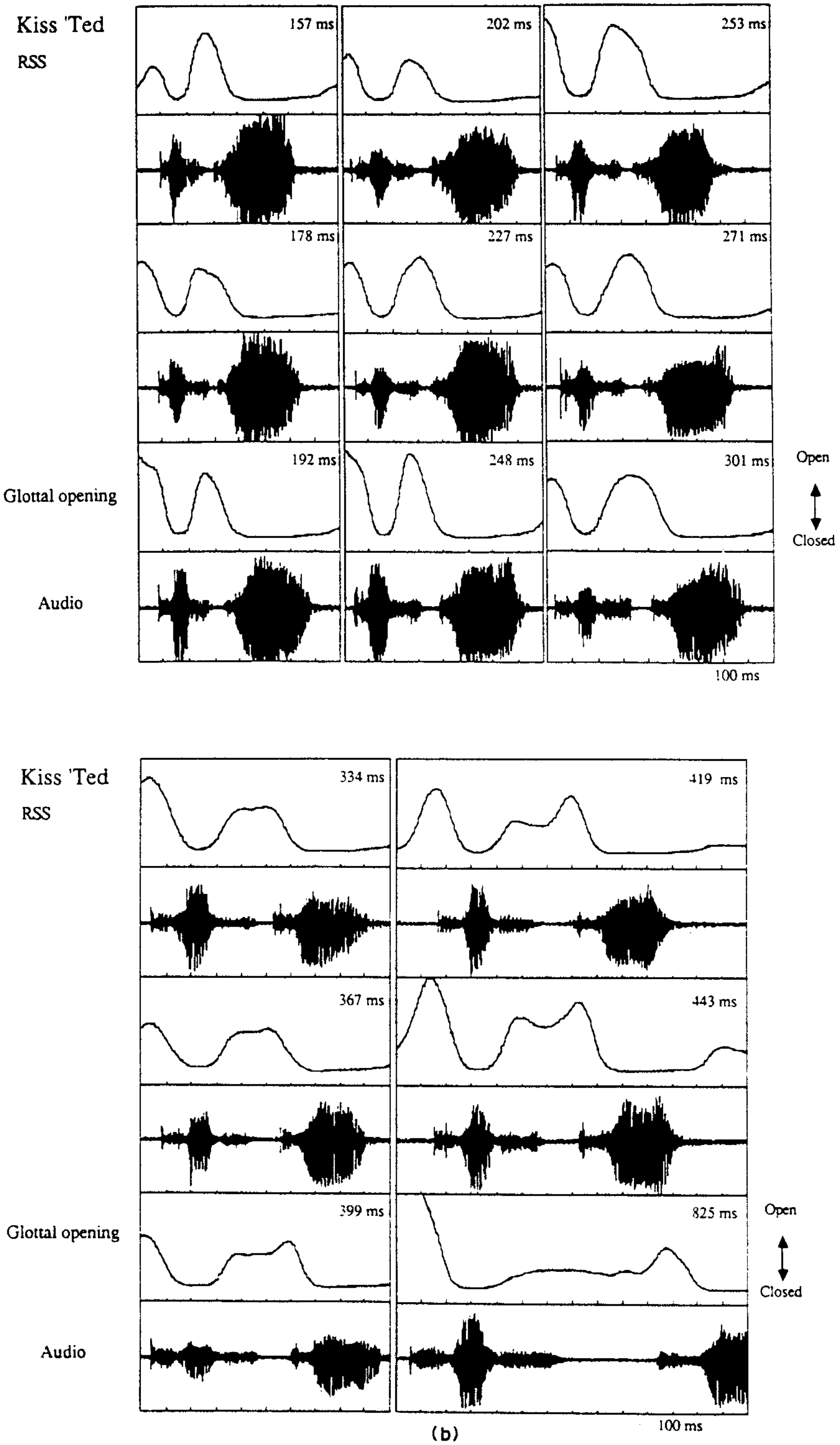

Figure 4—*contd*.

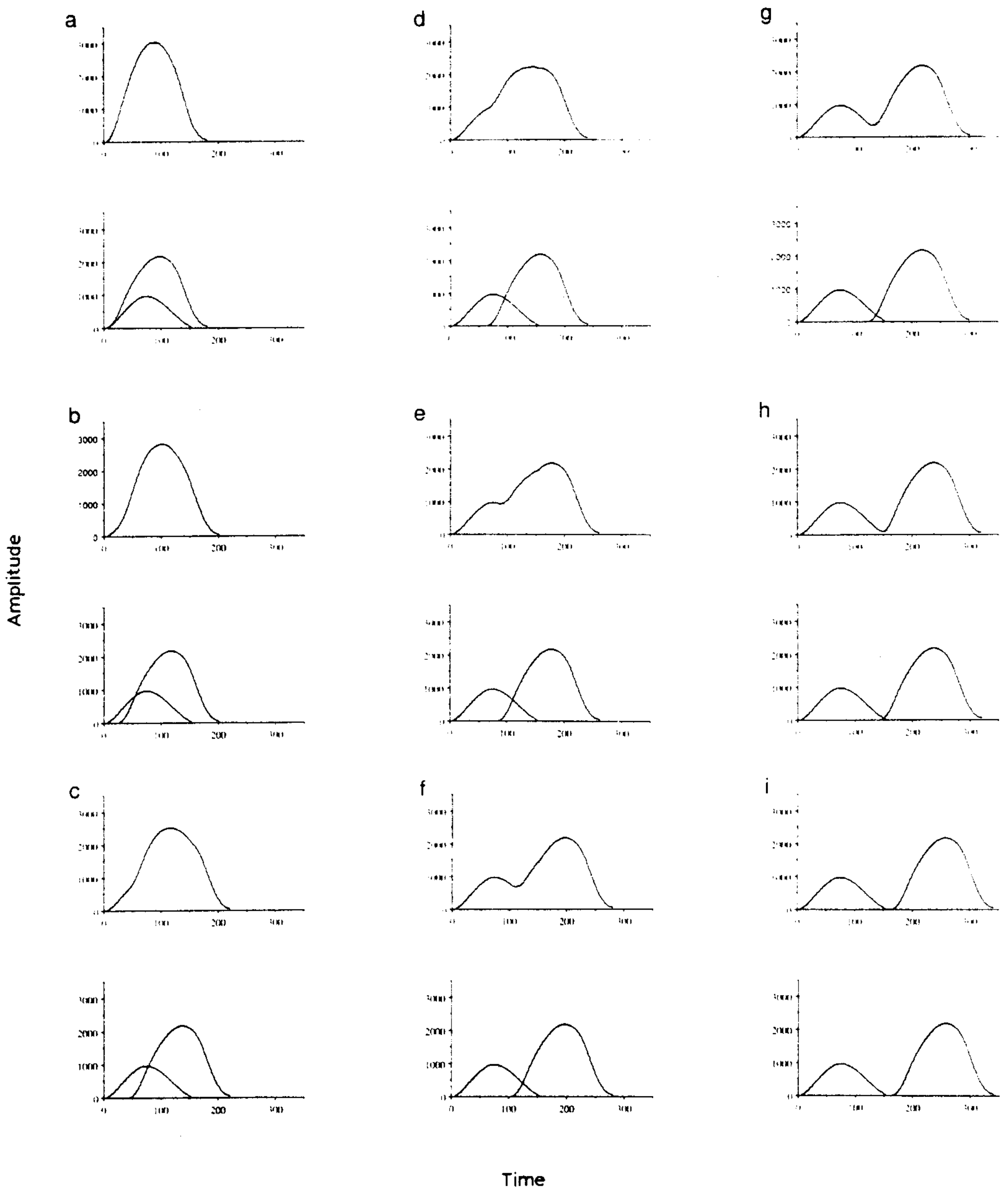

Figure 5. Simulations of the summations of two independent laryngeal gestures produced by KM arranged in order of decreasing overlap. The top graph of each pair shows the resulting waveform from the summation while the bottom graph shows the overlap that produced the composite movement.

Not only does the aggregation of the underlying gestures produce a single movement at the fastest rate but at the intermediate rates the simulations produce the partial blends observed in the data.

A second feature of the simulations does not seem to be well matched in the data. If the combination process for the movements was only a simple summation, an

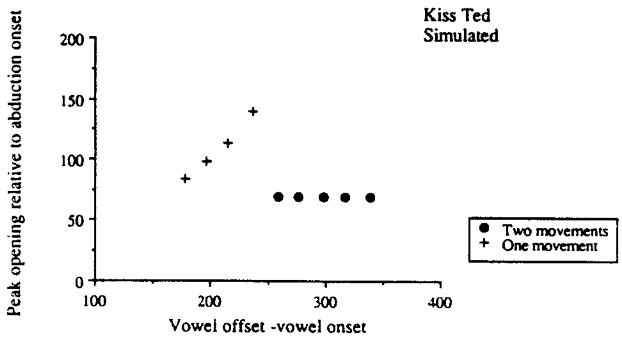

Figure 6. Plot of the simulated interval from vowel offset to vowel onset against the simulated position of peak glottal opening relative to the onset of the abduction for the fricative.

increase in amplitude of the laryngeal movements would be observed as the two underlying gestures were added. Looking at the data presented for subject KM in Fig. 4, we see that the size of the fused gestures (the panels going from 257 to 370 ms vowel offset-vowel onset interval) tends to be larger than that of the individual gestures at 439 ms vowel offset-vowel onset interval. At even faster rates for this subject (KM), however, the amplitude of the movement tends to decrease. This is presumably due to the general tendency for movement amplitudes to be reduced at faster rates of speaking (e.g., Ostry & Munhall, 1985). The results for subject RSS in Fig. 4 do not, however, show the same pattern. Here, the amplitude of the combined gestures is not necessarily larger than that of the individual gestures.

Finally, we can use the simulation to examine the timing patterns shown in Fig. 3. In Fig. 6, the interval from the onset of abduction of the first gesture to the offset of adduction of the final gesture is plotted against the interval from abduction onset of the first gesture to the first peak opening. These are equivalent to the intervals plotted in Fig. 3. There is a striking similarity between the observed data for KM and the simulated patterns. In both cases, the interval between peak opening and frication/abduction onset shows little or no change as a function of speaking rate/degree of overlap for the two laryngeal movement trials. However, when only a single movement is found, the relationship between the two intervals changes in both the simulated and observed data. In particular, a discontinuity is observed in the function as the two underlying gestures blend to form a single movement pattern. For subject RSS, the match of the simulation to the observed two movement pattern is less perfect. In her data, the two-movement trials show a more marked regression between peak opening to frication onset and vowel offset to vowel onset than is observed in the simulations. However, RSS shows the same discontinuity as is observed in the simulations when the one movement patterns are plotted.

4. Discussion

The kinematic patterns in the present data closely resemble those reported by Löfqvist & Yoshioka (1981). At slow rates two separate laryngeal movements were observed while at fast rates only a single laryngeal movement was produced for the two intervocalic obstruents. In trials that were intermediate in rate the transillumination shapes suggested that two underlying movements were being combined. This interpretation was supported by a simulation in which overlapping gestures were added.

While the simulated and observed movement patterns show good agreement not all issues are resolved by these data. The status of single peak movements, in particular, is not certain. At least two possibilities exist. First, the fastest utterances that exhibit only a single smooth glottal movement could still be composed underlyingly of two separate laryngeal gestures. Such a position has recently been taken by Saltzman & Munhall (1989) for within-word fricative-stop clusters. On the other hand, at some degree of overlap a reorganization may occur and a single laryngeal movement may be "programmed". At first blush, the existence of intervowel durations where both one and two peaked movements are observed suggests that two methods of coordination are at the speakers' disposal here. Some factors argue against this interpretation. Determining whether one or two glottal peaks exists is quite difficult in the region where the two patterns are both observed. As can be seen in Fig. 4, in some of the intermediate-rate utterances plateaus in the laryngeal signal are observed. It is clear that in trials like these, small differences in the signal could determine whether one or two peaks were classified. For example, subtle changes in emphasis, speaking style, etc., could change the relative amplitudes of the two underlying glottal gestures and therefore the form of the composite movement. In the region of change from one to two movements this type of production variability could cause the observed pattern.

One problem in the area of coarticulation and in the present study is that it is difficult, in practice, to distinguish between alternative explanations. At the fastest speaking rates in the present data, a single movement is observed. By examining the kinematics of these movements in isolation it is impossible to determine the nature of the underlying control signal. For two reasons, we have favored the overlap account for the present data. While any individual movement could be accounted for by many approaches, it is more parsimonious to attribute all of the data to a single pattern of serial ordering. It would appear, particularly from the intermediate rate observations, that two separate gestures are blended. This style of coordination can produce the full range of observed data and thus seems a likely candidate even for the fastest speaking rates. A second factor that supports this approach is evidence from other motor activities.

In the study of nonspeech movements several similar summation effects have been described. In a model proposed by Bullock & Grossberg (1988), for example, rate dependent changes in the velocity profile of movements are accounted for by the "truncation" of a movement by the activation of a following movement. In this model, the deceleration of movements is altered if a following movement begins before the first movement has run its course. The effects of both movements are blended with the net effect that the first movement is truncated. As indicated in the Introduction, the adjustments observed in the trajectories of precise aiming movements and in slow movements of the limbs can be modeled well by assuming that submovements are superimposed to create the observed movement (Milner & Ijaz, 1990). In these movements, adjustments are made during the course of a trajectory and the independent movement impulses appear to be superimposed to yield the overall movement pattern. In aiming movements this involves the superposition of small terminal adjustments on the end of a larger initial movement but in slow movements a number of overlapping impulses of equal size can account for the observed velocity patterns. Finally, Flash (1990; Flash & Henis, in press) has shown superposition effects when a second movement must begin at unexpected times during the production of an initial movement. In her task, arm movements were studied when the location of a target was unexpectedly changed on some trials after the movements had already begun. Her data suggest that the first movement to the original target position is not aborted but is blended with the second movement towards the new target position. The resulting tangential velocity was well approximated by adding the two underlying movements. The movements in all of these instances exhibit the same parallel behavior even though the source of the overlap is quite different. We would like to suggest that movement sequencing in speech and other activities such as error correction in arm movements share a common scheme for implementing successive movement elements. The cause and timing of the overlap may be independent of the manner in which the nervous system ultimately implements the movements.

The present results show a pattern similar to the trough phenomenon (e.g., Gay, 1978; McAllister, 1978; Engstrand, 1981; Perkell, 1986) reported for lip movements. For a consonant assumed to be unspecified for labial activity occurring between two rounded vowels, it has been shown that the lips do not maintain a steady rounded position but are retracted for the medial consonant. In the present data, the glottis does not open only once and maintain a static open position throughout the voiceless consonants. The laryngeal articulatory movements are organized in one or more opening and closing movements and it is almost never the case that the glottis stays in a static open position. While this may be a particular feature of laryngeal articulatory control, it is reasonable to extend the argument for simple combination that we have made for laryngeal control to cover also the upper articulators. Under this view, the trough results from two, or more, gestures being blended. A further prediction is that the presence and absence of the trough as well as its articulatory characteristics should be related to speaking rate. Although this specific prediction has not been experimentally tested, material on labial coarticulation presented by Boyce (1988) is in agreement with this prediction. Further, Boyce was able to decompose the labial activity for VCV sequences into underlying components for the vowels and medial consonants respectively. In addition, data on velar movements presented by Boyce, Krakow, Bell-Berti & Gelfer (1990) suggest that the occurrence of a one- or two-movement pattern of the velum is affected by speaking rate; a one-movement pattern is more often found at fast speaking rates.

The patterns of muscular activity in the lip and velar patterns are not well understood. For the larynx, however, electromyographic results presented by Löfqvist, McGarr & Honda (1984) indicate that when a succession of glottal abduction and adduction movements occurs, the abductions are associated with activity in the posterior cricoarytenoid muscle, while the adductions are correlated with activity in the vocalis muscle. It will be important to pursue this issue with stimuli such as those used in the present study.

A number of years ago, Lindblom (1963) suggested that one of the determinants of acoustic duration change with increased speaking rate was that the articulatory system failed to complete one movement before the next excitation signal arrived.

In cases such as this the articulators could be "responding to several signals simultaneously". Recently, Munhall, Fowler, Hawkins & Saltzman (1989) have argued that conditions very much like those proposed by Lindblom account for the shortening of the jaw trajectory for vowel production when consonants are added to the coda of a syllable. The underlying jaw lowering trajectory is not altered but the raising for the following consonant starts earlier when the coda contains more consonants and thus the raising and lowering movements are combined. Beckman, Edwards & Fletcher (in press) have argued that a similar pattern of differences in the relative overlap of jaw-opening and jaw-closing gestures accounted for the differences observed in accented *vs.* unaccented syllables.

While Lindlom's (1963) intuitions about the effects of this timing overlap seem correct, there is less reason to adopt the precise physiological explanation proposed in that paper. Combinations in speech and other movements could occur at a number of levels in the production system ranging from the motor cortex to the alpha motoneuron pool. Kinematically the results would be indistinguishable. In fact, even if no neural or myoelectric summation occurred, the dynamics of the articulators would ensure a gradual blending of influences.

We have suggested that some form of blending of gestures may be a more general phenomenon that has a number of possible advantages. Foremost amongst these is computational simplicity. In other biological phenomena similar aggregation processes are evident. Neuronal excitation is one obvious example. The algebraic sum of excitatory inputs must exceed a threshold for a voltage spike to be produced. The behavior of reflex response fields in various lower vertebrates also shows some form of blending behavior (e.g., Berkinblit, Feldman & Fukson, 1986; Stein, Mortin & Robertson, 1986).

If simple summation is such a general phenomenon, why do the laryngeal data not always correspond with the prediction that an increase in the glottal opening should be observed as the two underlying movements are combined? There are two possible explanations. One possibility is that the instruction to increase rate, (the manner in which the overlap of the two gestures was induced) is also modifying the form of the laryngeal gestures. Rate can cause decreases in movement size and thus a more exact modeling of the data would require at least two parameters, one associated with the rate of a single gesture and one associated with the relative timing of successive gestures (cf. Beckman *et al.*, in press; Saltzman & Munhall, 1989).[1] The present experiment, unlike the start-a-new-movement paradigm employed by Flash (1990), confounds these two parameters. On the other hand, it may be that the instability of transillumination across trials makes the amplitude information unreliable. To our knowledge, the dynamic stability of the transillumination signal has never been assessed in detail. However, preliminary analysis of data comparing productions of *Kiss Ted* and *Kiss Ed* show that the area under the transillumination curve decreases continuously with speaking rate for both utterance types but that the *Ted* utterances have a larger area at at all speaking rates than the *Ed* utterances at all speaking rates. Two things are important here. First, the decrease in area is continuous for the *Ted* utterances, showing no sudden change

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[1] One way to reduce the problem to a single parameter linked to rate would to be have the onset of laryngeal adduction slide with respect to abduction. In faster movements, onset of closing would occur during the time course of the opening movement and thus alter the duration and amplitude of the glottal movement.

in amplitude as the movements overlap. Second, the size difference for the cluster over the singleton is maintained even at faster rates of speaking.

In summary, the present data suggest to us that at least one type of coarticulation can be implemented in a manner that requires little active reorganization. This movement summation is a general strategy that is apparently utilized in many kinds of movements and articulatory systems to accommodate sequences produced with variable time scores.

This work was supported by grants from the Ontario Ministry of Health and the Natural Sciences and Engineering Research Council of Canada to K. G. Munhall, and by NIDCD Grant DC-00865, and BRS Grant RR-05596 to Haskins Laboratories. The authors would like to thank John Westbury, Mary Beckman, and two anonymous reviewers for helpful comments on an earlier draft of this manuscript.

References

Baer, T., Löfqvist, A. & McGarr, N. S. (1983) Laryngeal vibrations: a comparison between high-speed filming and glottographic techniques, *Journal of the Acoustical Society of America*, **73**, 1304–1308.

Beckman, M., Edwards, J. & Fletcher, J. (in press) Prosodic structure and tempo in a sonority model of articulatory dynamics. In *Papers in laboratory phonology II: segment, gesture, tone* (G. Docherty & D. Ladd, editors). Cambridge: Cambridge University Press.

Bell-Berti, F. & Harris, K. S. (1979) Anticipatory coarticulation: Some implications from a study of lip rounding, *Journal of the Acoustical Society of America*, **65**, 1268–1270.

Bell-Berti, F. & Harris, K. S. (1982) Temporal patterns of coarticulation: Lip rounding, *Journal of the Acoustical Society of America*, **71**, 449–459.

Benguerel, A.-P. & Cowan, H. (1974) Coarticulation of upper lip protrusion in French, *Phonetica*, **30**, 9–20.

Benoit, C. (1986) Note on the use of correlation in speech timing, *Journal of the Acoustical Society of America*, **80**, 1846–1849.

Berkinblit, M., Feldman, A. & Fukson, O. (1986) Adaptability of innate motor patterns and motor control. *Behavioral and Brain Sciences*, **9**, 585–638.

Boyce, S. (1988). The influence of phonological structure on articulatory organization in Turkish and English vowel harmony and coarticulation. Unpublished doctoral dissertation, Yale University.

Boyce, S. E., Krakow, R., Bell-Berti, F. & Gelfer, C. (1990) Converging sources of evidence for dissecting articulatory movements into core gestures, *Journal of Phonetics*, **18**, 173–188.

Bullock, D. & Grossberg, S. (1988) The VITE model: a neural command circuit for generating arm and articulator trajectories. In *Dynamic Patterns in Complex Systems* (J. A. S. Kelso, A. J. Mandell & M. F. Shlesinger, editors, pp. 305–326. Singapore, World Scientific Publishers.

Daniloff, R. & Moll, K. (1968) Coarticulation of lip-rounding, *Journal of Speech and Hearing Research*, **11**, 707–721.

Engstrand, O. (1981) Acoustic constraints of invariant input representation? An experimental study of selected articulatory movements and targets, *Reports* (*Department of Linguistics, Uppsala University*), **7**, 67–94.

Fant, G. (1962) Descriptive analysis of the acoustic aspects of speech, *Logos*, **5**, 3–17. (Reprinted in G. Fant (1973) *Speech Sounds and Features*, pp. 17–31 (Cambridge, Mass.: MIT Press.)

Flash, T. (1990) Organization of human arm trajectory control. In *Multiple Muscle Systems: Biomechanics and Movement Organization* (J. Winters & S. Woo, editor). New York: Springer.

Flash, T. & Henis, E. (in press) Arm trajectory modification during reaching towards visual targets, *Journal of Cognitive Neuroscience*.

Fowler, C. (1980) Coarticulation and theories of extrinsic timing, *Journal of Phonetics*, **8**, 113–133.

Gay, T. (1978) Articulatory units: Segments or syllables? In *Syllables and segments* (A. Bell & Hooper, editors). Amsterdam: North-Holland.

Henke, W. (1966) *Dynamic articulatory model of speech production using computer simulation.* Unpublished doctoral dissertation. MIT.

Kozhevnikov, V. & Chistovich, L. (1965) *Speech: Articulation and Perception.* Joint Publications Research Service, 30,543; U.S. Department of Commerce.

Lindblom, B. (1963) A spectrographic study of vowel reduction, *Journal of the Acoustical Society of America*, **35**, 1773–1781.

Lubker, J. (1981) Temporal aspects of speech production: anticipatory labial coarticulation, *Phonetica*, **38**, 51–65.

Lubker, J. & Gay, T. (1982) Anticipatory labial coarticulation: experimental, biological, and linguistic variables, *Journal of the Acoustical Society of America*, **71**, 437–447.

Löfqvist, A., McGarr, N. S. & Honda, K. (1984) Motor control of laryngeal articulation, *Journal of the Acoustical Society of America*, **76**, 951–954.

Löfqvist, A. & Yoshioka, H. (1980) Laryngeal activity in Swedish obstruent clusters, *Journal of the Acoustical Society of America*, **68**, 792–801.

Löfqvist, A. & Yoshioka, H. (1981) Laryngeal activity in Icelandic obstruent production, *Nordic Journal of Linguistics*, **4**, 1–18. (Also published in *Haskins Laboratories: Status Report on Speech Research SR-63/64*, 1980 275–292.)

McAllister, R. (1978) Temporal asymmetry in labial coarticulation, *Working Papers (Institute of Linguistics, Stockholm University)*, **35**, 1–29.

MacNeilage, P. (1970) Motor control of serial ordering of speech, *Psychological Review*, **77**, 182–196.

McNeilage, P. & DeClerk, J. (1969) On the motor control of coarticulation in CVC monosyllables, *Journal of the Acoustical Society of America*, **45**, 1217–1233.

Milner, T. E. & Ijaz, M. (1990) The effect of accuracy constraints on three-dimensional movement kinematics, *Neuroscience*, **35**, 365–374.

Morasso, P. (1986) Trajectory formation. In *Human Movement Understanding* (P. Morasso & V. Tagliasco, editor) New York: North Holland.

Munhall, K. G. (1985) An examination of intra-articulator relative timing, *Journal of the Acoustical Society of America*, **78**, 1548–1553.

Munhall, K. G. & Löfqvist, A. (1987) Gestural aggregation in speech, *PAW Review*, **2**, 13–15.

Munhall, K. G. & Ostry, D. (1985) Ultrasonic measurement of laryngeal kinematics. In *Vocal Fold Physiology* (I. Titze & R. Scherer, editors), pp. 145–162. Denver: Denver Center for the Performing Arts.

Munhall, K. G., Fowler, C., Hawkins, S. & Saltzman, E. (1989) Compensatory shortening in English monosyllables (submitted).

Öhman, S. (1966) Coarticulation in VCV utterances: Spectrographic measurements, *Journal of the Acoustical Society of America*, **39**, 151–168.

Öhman, S. (1967) Numerical model of coarticulation, *Journal of the Acoustical Society of America*, **41**, 310–320.

Ostry, D. & Munhall, K. G. (1985) Control of rate and duration of speech movements, *Journal of the Acoustical Society of America*, **77**, 640–648.

Perkell, J. (1986) Coarticulation strategies: Preliminary implications of a detailed analysis of lower lip protrusion movements, *Speech Communication*, **5**, 47–68.

Saltzman, E. & Munhall, K. (1989) A dynamical approach to gestural patterning in speech production, *Ecological Psychology*, **1**, 333–382.

Stein, P., Mortin, L. & Robertson, G. (1986) The forms of a task and their blends. In *Neurobiology of vertebrate locomotion* (S. Grillner, P. Stein, D. Stuart, H. Forssberg & R. Herman, editors), pp. 201–216. London: Macmillan.

Stevens, K. & House, A. (1963) Perturbations of vowel articulations by consonantal context: an acoustical study, *Journal of Speech and Hearing Research*, **6**, 111–128.

Stevens, K., House, A. & Paul, A. (1966) Acoustic description of syllable nuclei: an interpretation in terms of a dynamic model of articulation, *Journal of the Acoustical Society of America*, **40**, 123–132.

Sussman, H. & Westbury, J. (1981) The effects of antagonistic gestures on temporal and amplitude parameters of anticipatory labial coarticulation, *Journal of Speech and Hearing Research*, **46**, 16–24.

Woodworth, R. S. (1899) The accuracy of voluntary movement, *Psychological Review*, **3**, 1–114.

Yoshioka, H., Löfqvist, A. & Hirose, H. (1981) Laryngeal adjustments in the production of consonant clusters and geminates in American English, *Journal of the Acoustical Society of America*, **70**, 1615–1623.