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Laryngeal Mechanisms and Interarticulator Timing in Voiceless Consonant Production

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INTRODUCTION

During speech, parts of the vocal tract are briefly coupled in a functional manner to produce the acoustic characteristics of speech sounds. For example, the production of the bilabial voiceless stop /p/ requires the following set of actions. The lips are closed by joint activity of the jaw and the lips. The velum is elevated to seal off the entrance into the nasal cavity. The glottis is widened and the longitudinal tension of the vocal folds is often increased to prevent glottal vibrations. These articulatory actions all contribute to the period of silence in the acoustic signal and the increase in oral air pressure that are associated with a voiceless stop consonant. Speech production thus involves control and coordination of different parts of the vocal tract. Variations in their timing and coordination are commonly used to produce linguistic contrasts. For example, in stop consonants timing is used to control voicing and aspiration. In the following, we shall review aspects of voiceless consonant production with particular emphasis on laryngeal mechanisms and the coordination between laryngeal and supralaryngeal events. The material will be discussed in relation to control of coordinated movements in general.

LARYNGEAL MECHANISMS

The larynx serves as the source for voiced sounds, controlling the amplitude, the fundamental frequency, and the spectral properties of the source. For voiceless consonants, the source has to be momentarily turned off and then turned on again for the following sound. Turning off the source is commonly made by opening the glottis. The glottal abduction-adduction movement is controlled by the intrinsic laryngeal muscles. The posterior cricoarytenoid (PCA) muscle controls abduction, while the interarytenoid (INT), the vocalis (VOC), and the lateral cricoarytenoid (LCA) muscles adduct the vocal folds. The cricothyroid (CT) muscle regulates the length and tension of the folds. Figure 1 presents records of glottal opening, obtained by transillumination of the glottis, and the electromyographic activity of the PCA and the INT muscles in the production of a voiceless fricative and a voiceless stop consonant; the signals represent averages of 10-15 repetitions. The glottal opening is constantly changing, first increasing and then decreasing. Shortly before the start of the opening gesture, the activity of the PCA begins to increase, while the INT shows a reciprocal decrease in activity. The latency between the recorded electromyographic activity and the resulting mechanical action is in the order of 50-100 ms. For the glottal adduction, the pattern of activity in the two muscles is reversed with a decrease in PCA and an increase in INT.

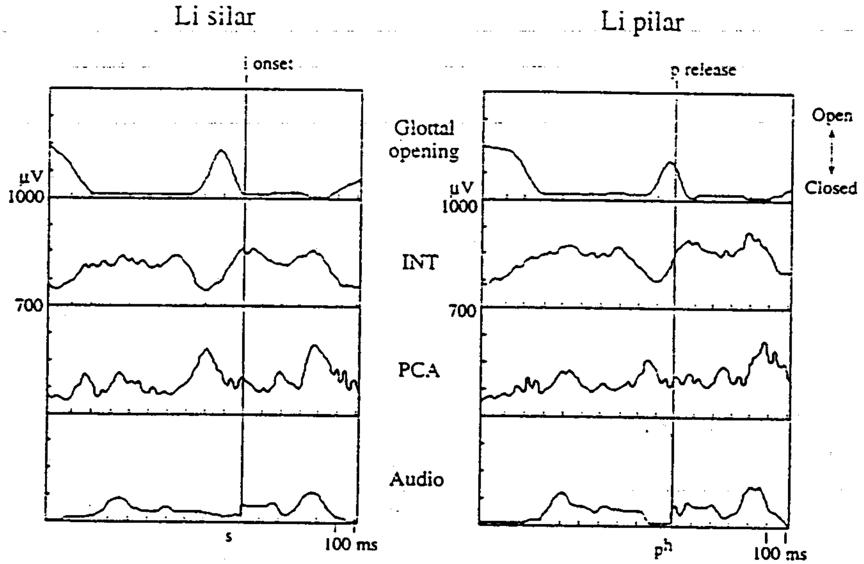

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FIGURE 1. Records of glottal opening, the activity of the INT and the PCA muscles, and the audio envelope during the production of utterances with a voiceless fricative and a voiceless stop. The vertical line marks the line-up point used for averaging 10-15 repetitions. (Modified from Löfqvist & Yoshioka, 1980.)

In clusters of voiceless consonants, the glottis may show several opening movements (e.g., Löfqvist & Yoshioka, 1980, 1981; Pétursson, 1976a; Yoshioka, Löfqvist, & Collier, 1982; Yoshioka, Löfqvist, & Hirose, 1981). Such a pattern is illustrated in Figure 2, showing glottal opening and PCA and INT activity in the clusters /sts/ and /sts#p/. Note, in particular, that separate openings occur for the voiceless fricative /s/ and word initial voiceless aspirated stop /p/; between these opening movements, the glottis is narrowed without complete closure. In these clusters, the activity of both the INT and the PCA changes to produce the variations in glottal opening.

Figure 3 shows the activity of the other intrinsic laryngeal muscles in the production of a voiceless and a voiced bilabial stop. The LCA, the VOC, and the CT muscles all show a peak of activity around the line-up point used for averaging. This increase is related to the stress pattern of the utterance, where sentential stress occurs on the first syllable of the second word; this syllable has a high fundamental frequency. The difference in the activity of the muscles related to the voicing distinction can be seen in a decrease of activity of the LCA, the VOC, and the INT for the voiceless consonant. Note, however, that the CT activity does not appear to decrease for the voiceless stop.

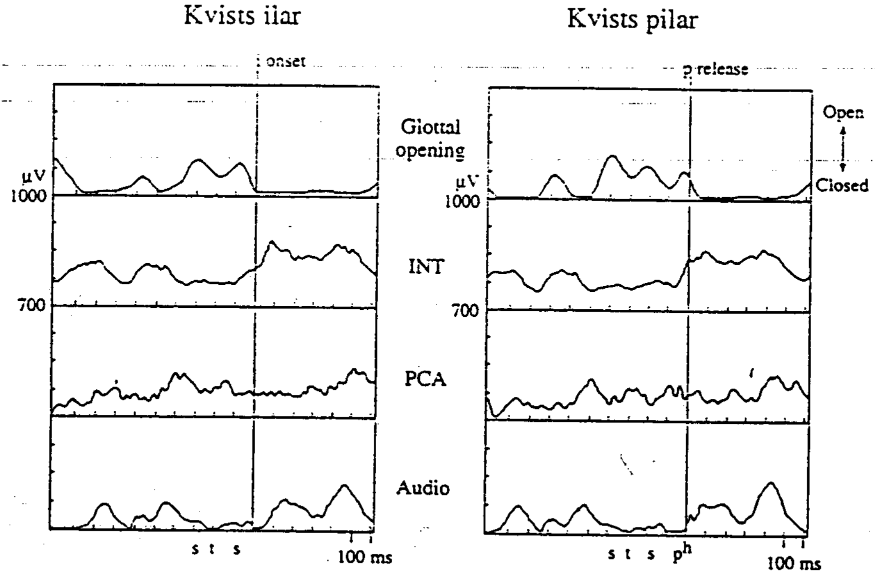

FIGURE 2. Records of glottal opening, the activity of the INT and the PCA muscles, and the audio envelope during the production of utterances with voiceless consonant clusters. The vertical line marks the line-up point used for averaging 10-15 repetitions. (Modified from Löfqvist & Yoshioka, 1980.)

In fact, a closer examination of the CT muscle suggests that it is activated more for voiceless than for voiced consonants, most likely to increase the longitudinal tension of the vocal folds and thus assist in the suppression of glottal vibrations (cf. Löfqvist, Baer, McGarr, & Seider Story, 1989). This mechanism can also account for the commonly observed high fundamental frequency at the beginning of a vowel following a voiceless stop or fricative.

The activity of several intrinsic laryngeal muscles in the production of voiceless consonant clusters is shown in Figure 4. From this figure, it is apparent that the activity of the VOC muscle successively increases and decreases in synchrony with the changes in the glottal opening. The continuous glottal adjustments in such consonant clusters are thus under active motor control as exemplified in Figures 2 and 4.

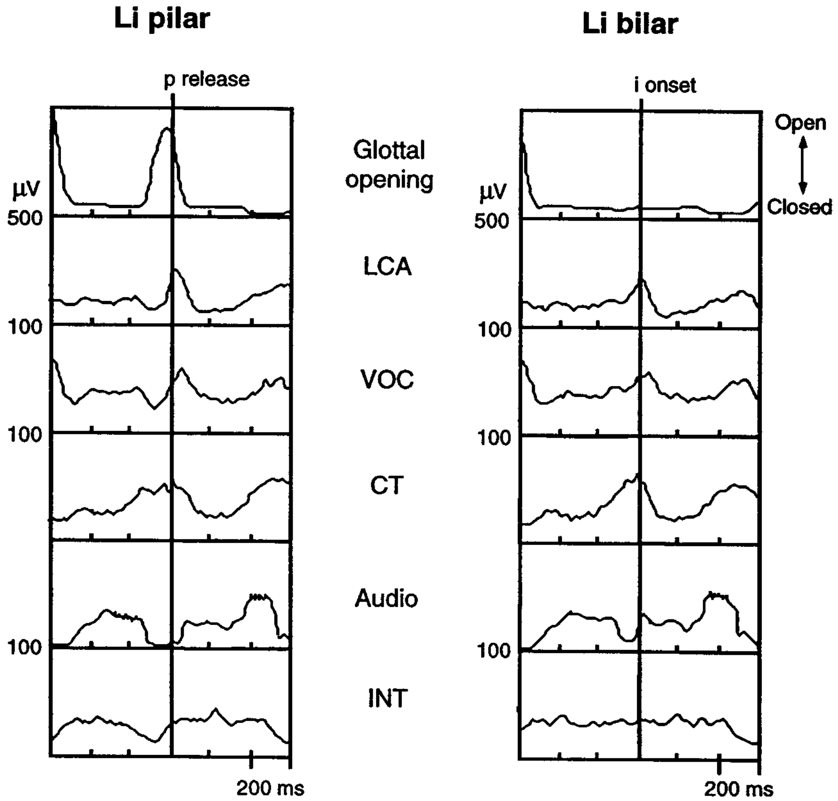

FIGURE 3. Records of glottal opening and the activity of the LCA, the VOC, the CT, the INT muscles, and the audio envelope during the production of utterances with a voiceless and voiced stop. The vertical line marks the line-up point used for averaging 10-15 repetitions. (Modified from Löfqvist, McGarr, & Honda, 1984.)

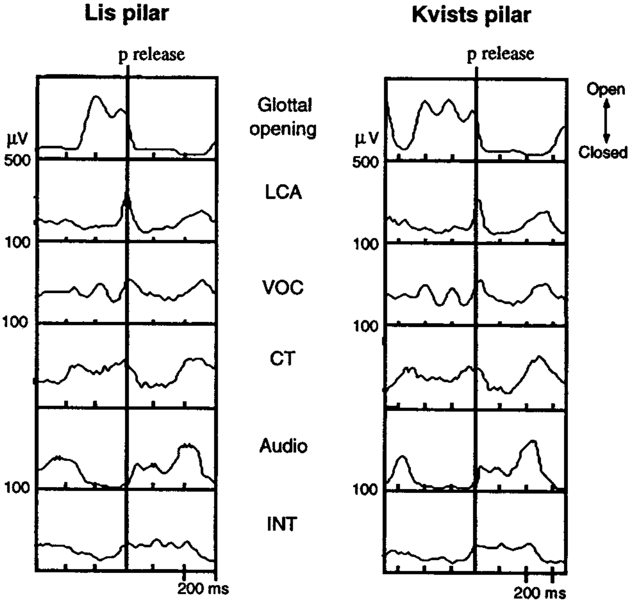

FIGURE 4. Records of glottal opening and the activity of the LCA, the VOC, the CT, the INT muscles, and the audio envelope during the production of utterances with voiceless consonant clusters. The vertical line marks the line-up point used for averaging 10-15 repetitions. (Modified from Löfqvist, McGarr, & Honda, 1984.)

There appear to be some differences in the glottal opening movement between voiceless stops and fricatives. Figure 5 shows glottal opening as a function of time during the production of a single voiceless fricative, a single voiceless aspirated stop, and a cluster of a voiceless fricative plus a voiceless unaspirated stop. The velocity of the opening change is also plotted. The size[1] of the opening is larger for the fricative than for the stop (cf. Munhall & Ostry, 1983; Gracco & Löfqvist, in press). Note that the movement is virtually identical for the single fricative and the cluster of fricative plus stop. In addition to the size difference, there is also a difference in the timing of the maximum opening relative to the offset of the preceding vowel: the maximum opening occurs closer to the vowel offset in the fricative than in the stop. The peak glottal opening corresponds to the onset of glottal adduction; it is under motor control and can be used as a reference point in studies of interarticulator timing. In the next section, we shall examine the timing between the laryngeal and oral articulatory movements in more detail.

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[1] It should be kept in mind that the transillumination signal is uncalibrated. Care is thus necessary in drawing conclusions about the size of the glottal opening. Measurements obtained by transillumination, however, show good agreement with those obtained using ultrasound (Munhall & Ostry, 1983).

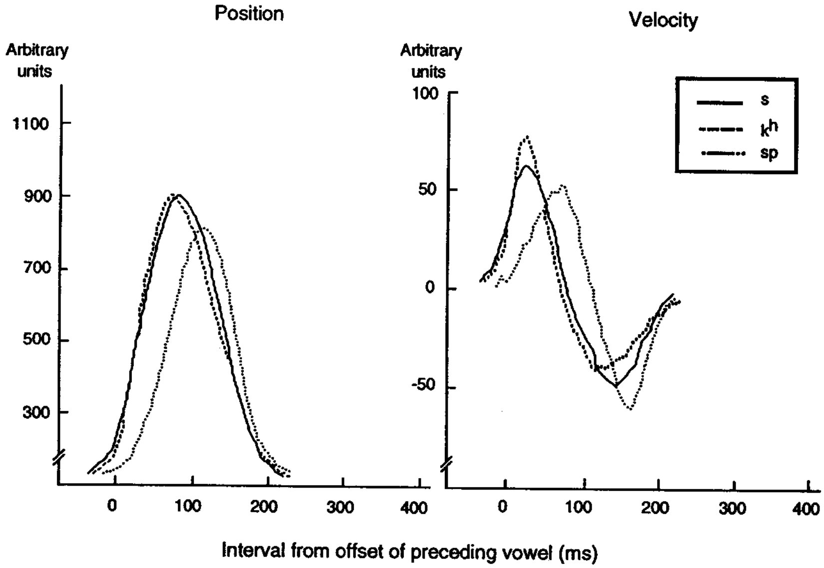

FIGURE 5. Records of the glottal opening movement during the production of different voiceless consonants. (Modified from Löfqvist & Yoshioka, 1981.)

INTERARTICULATOR TIMING

The production of voiceless consonants requires a tight coordination between the oral and laryngeal movements. First, at the transition from a preceding vowel to a voiceless consonant, the onset of glottal abduction has to be coordinated with the onset of the oral closure or constriction. Second, at the transition from the voiceless consonant to a following vowel, the onset of glottal adduction has to be coordinated with the release of the closure/constriction so that the glottal vibrations start at the appropriate time. It is well established that variations in the relative timing of the oral and laryngeal events are used to control voicing and aspiration in stop consonants. For example, if the onset of the glottal gesture precedes the formation of the oral closure, the last part of the preceding vowel is produced with a voice source that is breathy. This pattern of coordination is observed in languages that have preaspirated stops, such as Icelandic and Irish (e.g., Pétursson, 1976b; Löfqvist & Yoshioka, 1981). The opposite pattern of coordination occurs in voiced aspirated stops, as in Hindi (Dixit, 1989). Here, the glottis begins to open near the end of the oral closure; the closure is thus voiced. The abduction-adduction gesture is then completed after the release of the oral closure, making the onset of the following vowel characterized by a breathy mode of phonation. Yet another timing pattern is observed in voiceless postaspirated stops. For these sounds, the onset of glottal abduction is synchronized with the onset of the oral closure; the closure is thus voiceless.

Glottal adduction starts at about the oral release. After the release, the vocal folds are being adducted while there is a high rate of air flow out of the vocal tract. As a result, the onset of glottal vibrations relative to the oral release is delayed while noise is being generated in the glottis.

Variations in laryngeal-oral coordination thus produce different acoustic and aerodynamic patterns in voiceless consonants (cf. Löfqvist & McGowan, 1992). Such differences are illustrated in Figure 6. Comparing the single voiceless stop /p/ with the stop in the cluster /sp/, we see that the glottal condition at the oral release is different in the two cases. For the single stop, the glottis is open at the release, while for the stop in the cluster, the glottis is closed at the release. The air flow after the release is higher for the single stop and the onset of glottal vibrations relative to the release is delayed compared to that following the stop in the cluster.

There has been some controversy about the nature of control of aspiration and Voice Onset Time (VOT, cf. Lisker & Abramson, 1964) in stop consonants (for reviews, see Abramson, 1977; Löfqvist, 1980; Dixit, 1989). The arguments have centered on the roles of laryngeal-oral timing and the size of the glottal opening. The currently received view would seem to suggest that differences in interarticulator timing are always found between stop categories differing in VOT, but that differences in the size of the glottal opening can also occur. However, most of the evidence for the role of interarticulator timing in the control of aspiration and VOT has been collected in studies comparing different stop categories, e.g., unaspirated vs. aspirated stops, mostly using average values.

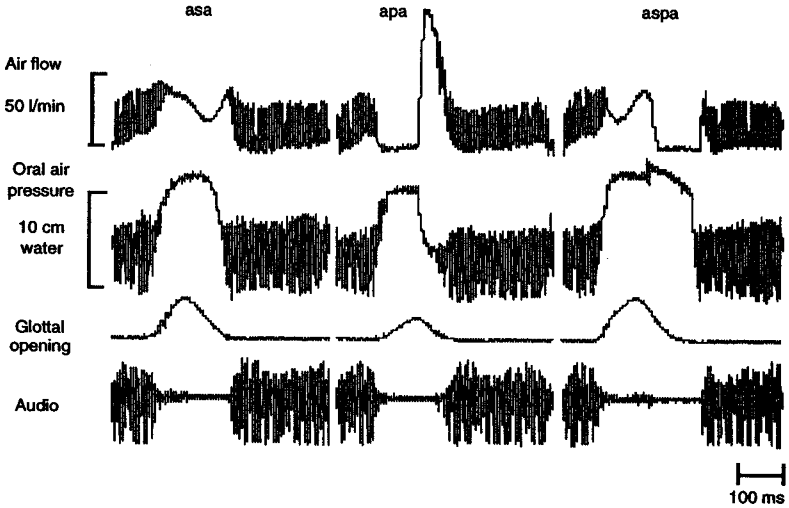

FIGURE 6. Records of air flow, oral air pressure, glottal opening, and the audio waveform during the production of different voiceless consonants. (Modified from Löfqvist, 1992.)

In fact, when the relation between oral-laryngeal coordination and VOT is examined across individual tokens, it turns out that the correlation between a measure of interarticulator timing and VOT is low, and that interarticulator timing explains less than 50% of the variance in VOT (Löfqvist, 1992). This finding suggests that, besides timing, aerodynamic and myodynamic factors also play a role in determining the onset of glottal vibrations following stop consonants. Among these factors are most likely the size of the glottal opening as well as the thickness and the viscosity of the vocal folds. Another implication is that fine-grained control of VOT may not be possible. This is probably not necessary, since languages do not appear to use fine-grained control of VOT for making linguistic distinctions. In the well-known case of Korean postaspirated stops, where there is a three-way distinction of VOT (short, medium, and long), an additional dimension commonly referred to as 'tensity' appears to be used (cf. Hirose, Lee, & Ushijima, 1974; Dart, 1987). The dimension of tensity is related to the force of glottal contact and is indexed by the activity of the VOC muscle.

Figure 7 plots the relation between the duration of the oral closure/constriction and the interval between onset of closure/constriction and peak glottal opening in voiceless stops and fricatives spoken at two different rates and under two different stress conditions (see Löfqvist & Yoshioka, 1984, for a more detailed description). For both the stops and the fricatives, there is a positive relation between the two temporal intervals, suggesting that they change together to maintain the relative phasing between the oral and laryngeal events. Also note that the relation between the two intervals differs between stops and fricatives. The slope of the regression between the variables is steeper for the stops than for the fricatives. Another difference in interarticulator timing is also evident from Figure 7. In the stops, which are all postaspirated, the onset of glottal adduction consistently occurs at about the release of the oral closure. For the fricatives, the same event occurs just before the middle of the oral constriction. These differences in interarticulator phasing are due to the different requirements in stop and fricative production, particularly the delay in voice onset after the stop release.

The temporal coordination between articulatory movements must be maintained within certain limits for speech to be intelligible, across changes in speaking rate. This requirement explains why the relations plotted in Figure 7 are positive. How this temporal cohesion is achieved, however, is not well understood. It has been suggested that variations in speaking rate result in a scaling between the different articulatory movements that are involved in the production process. This suggestion is based on the following theoretical view. If someone is writing a word on a paper with a pencil or on a blackboard with a piece of chalk, different parts of the body are used. When the word is written on paper, writing involves movements of the hand around the wrist; when it is written on the blackboard, the arm moves around the shoulder joint. Since the written pattern on the blackboard can be seen as a scaled version of the one on paper, it has generally been argued that there is a single underlying representation of the movement pattern that is instantiated by different parts of the body using a scaling relation (cf. Wright, 1990). The alternative view, that each pattern is stored as a separate entity, is at least intuitively implausible and inefficient. Thus, the claim is that the pattern is stored as a "generalized motor program" that can be reparameterized (see Schmidt, 1975). A generalized motor program predicts that when variations in speed and amplitude of a movement complex occur, the relations among the individual movements should remain virtually unchanged.

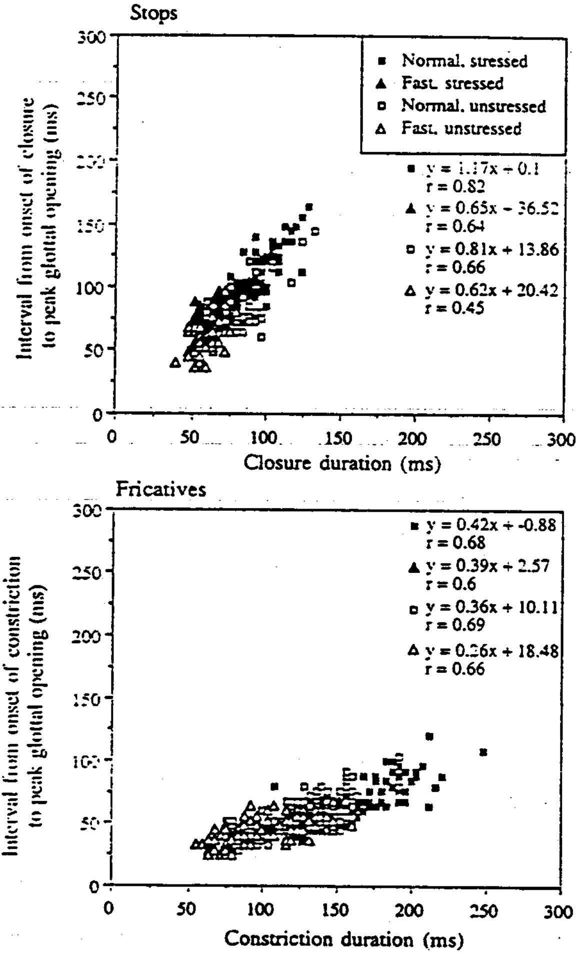

FIGURE 7. Plots of the duration of the oral closure/constriction and the interval from onset of closure/constriction to peak glottal opening in voiceless stops and fricatives (Modified from Löfqvist & Yoshioka, 1984.)

The reason is that a submovement interval should maintain a constant proportion of the whole movement interval. Hence, the model is usually referred to as a proportional duration model (see Heuer, 1991, for a general discussion of such models). Initially, several studies claimed that proportional timing was indeed found for motor activities like locomotion (Shapiro, Zernicke, Gregor, & Diestel, 1981), handwriting (Viviani & Terzuolo, 1980), typing (Terzuolo & Viviani, 1979), and speech (Tuller & Kelso, 1984).

Gentner (1987) proposed a stronger test of proportional duration by examining if the ratio between the duration of one movement interval and that of the whole movement sequence is unrelated to the duration of the whole movement sequence. The proportional duration model predicts that these should be related, since the duration of all the components of a movement sequence should maintain a constant proportion of the overall duration. Studies applying this statistical analysis suggest that proportional timing does not occur in speech or any other motor activity that has been examined (cf. Löfqvist, 1991; Sock, Ollila, Delattre, Zilliox, & Zohair, 1988; Wann & Nimmo-Smith, 1990). The slope of the regression usually deviates from zero. An examination of the data plotted in Figure 7 for constant proportionality shows that the slope of the regression between closure duration and the ratio of time to peak opening and closure duration is significantly different from zero for the stressed stops and the fricatives but not for the unstressed stops; for the latter, the lack of a statistically significant effect is due to a large variability in the data (see Löfqvist, 1991, for a more detailed discussion). One methodological uncertainty facing students of speech timing should be mentioned in this context. Studies of temporal phenomena by necessity must break up the flow of articulatory movements into discrete intervals for measurement. To delimit these intervals, movement onset and offset, and peak velocity of movement are commonly used. It is, of course, possible that these events are not the ones that the nervous system uses for controlling movements. Kelso, Saltzman, and Tuller (1986) suggested that the proper metric for constant relative timing is phase as measured on a phase plane, rather than ratio of articulatory intervals, and presented some evidence in support of this notion. In a phase-plane representation, position is plotted against velocity. In a vowel-labial consonant-vowel sequence, a phase-plane plot of the jaw or the lower lip shows an elliptical orbit. Using this kind of representation, movement onsets for different articulators can be defined in terms of phase relations. Further studies have, however, failed to replicate their findings (Lubker, 1986; Nittrouer, 1991; Nittrouer, Munhall, Kelso, Tuller, & Harris, 1988).

The data plotted in Figure 7 were based on measurements of movement onsets and offsets. Figure 8 illustrates laryngeal-oral coordination in voiceless consonant production from a different perspective. The bottom panel of this figure shows a plot of articulatory intervals during several normal productions of the utterance "It's a sifting again." The top panel shows how these intervals have been defined. The interval plotted along the x axis is measured from the peak glottal opening for the voiceless consonant cluster in "It's" (identified by the vertical dotted line in the top panel) to the peak velocity of the lower lip raising movement for the labiodental fricative /f/ in "sifting." On the y axis is plotted the interval from the same instance of peak glottal opening to the peak velocity of the glottal abduction movement for the fricative+stop sequence in "sifting." The movements of the lower lip and the glottis are both integral parts of the fricative. The intervals plotted in Figure 8 are thus temporally related to each other in the production of the specific utterance, and one would expect that they should covary. As variations in the overall duration of the utterance occur between productions, the intervals measured for the lower lip and the larynx should change together; remember that they have been measured from the same temporal reference point, peak glottal opening for the voiceless consonant cluster in "It's." As is evident from Figure 8, this is indeed the case. Their covariation can be indexed by the high correlation between them. At the same time, it is also apparent from Figure 8 that they do not scale proportionally, since the intercept of the regression is not at, or close to, zero.

A comparison of the correlation coefficients in Figures 7 and 8 shows that they are higher in Figure 8. The measurements shown in Figure 8 were made using peak velocity of movements as reference points, while those in Figure 7 were based on movement onsets and offsets. As noted above, it is not clear what peripheral events are the most revealing from the point of view of motor control. The higher correlations between temporal intervals defined by peak velocities may suggest that they are more useful for studying speech motor control. It is possible, however, that this is simply due to a methodological problem. That is, peak velocities may be more reliably identified in movement records than onsets and offsets, which are usually defined by zero crossings in the velocity signals.

Studying speech movements across changes in stress and speaking rate can provide insights into the mechanisms controlling the movements. Another valuable experimental paradigm for understanding movement coordination and control is to introduce unexpected perturbations to motor acts in a systematic manner. In a standard experiment, a subject is attached to a small motor that can be activated during some trials to generate a brief load. The rationale for this research is that the nature and time course of the response to the load may reveal the motor organization and reflex structure of the motor act. This paradigm has been applied to different types of motor behavior in humans such as posture control (e.g., Nashner & McCollum, 1985), hand and finger movements (e.g., Abbs, Gracco, & Cole, 1984; Rothwell, Traub, & Marsden, 1982; Traub, Rothwell, & Marsden, 1980), and respiratory control (Newsom Davis & Sears, 1970). A number of studies have also used this method to study speech motor control (Abbs & Gracco, 1984; Folkins & Abbs, 1975; Folkins & Zimmermann, 1982; Gracco & Abbs, 1985, 1988, 1989; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984; Kollia, Gracco, & Harris, 1992; Munhall, Löfqvist, & Kelso, 1994; Shaiman, 1989; Shaiman & Abbs, 1987).

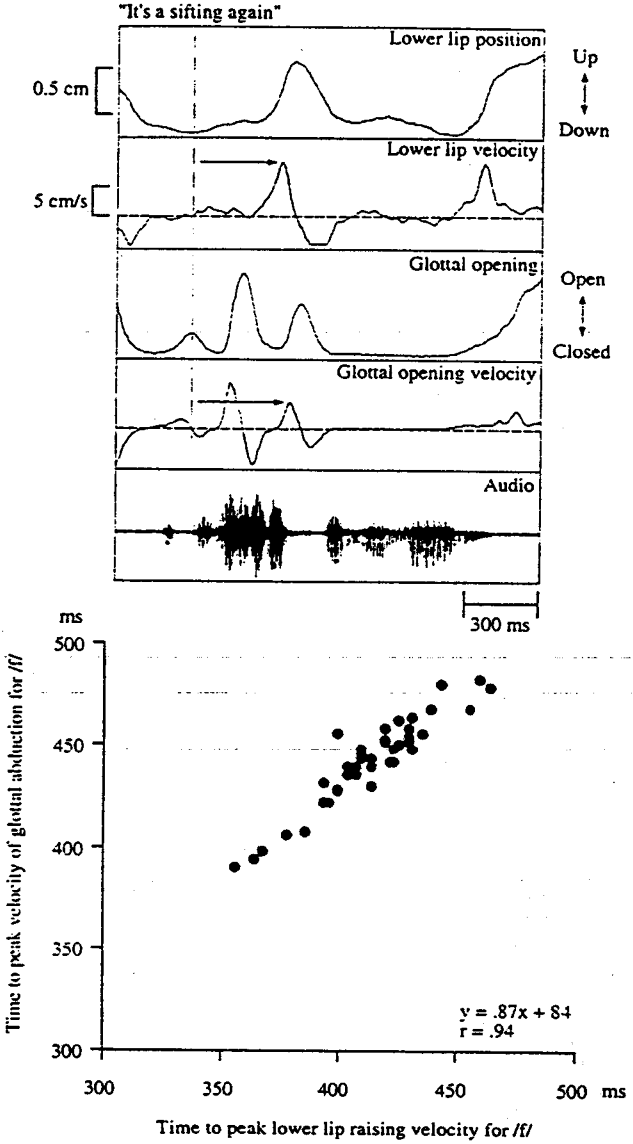

FIGURE 8. The top panel shows a single production of the utterance "It's a sifting again." The signals represent lower lip, glottal opening, and audio. Two articulatory intervals are defined that are related to the production of the labial fricative /f/ in the word "sifting." The bottom panel plots these two articulatory intervals. See text for further details.

From these speech perturbation studies, some general conclusions can be drawn. First, compensations are rapid. Electromyographic responses can occur 20-30 ms after load onset. The latency is not fixed, however, but depends on when the load was applied with respect to onset of activity in the muscles responsible for the movement in question (Abbs et al. 1984). Such short latencies suggest that the responses are not due to reaction time processes. Second, compensations are mostly task-specific. That is, they are neither stereotypic nor evident throughout the system, but rather tailored to the needs of the ongoing motor act. For example, when the jaw is loaded during the transition from a vowel to a bilabial stop, compensatory responses are made in the upper and lower lips to achieve the labial closure. On the other hand, when the jaw is loaded during the transition from a vowel to a dental fricative or a dental stop, a response is seen in the tongue (Kelso et al., 1984; Shaiman, 1989). We should add a word of caution here, however, since task specificity is not always consistent across speakers. In particular, one of the subjects in the study by Shaiman (1989) showed increased lower lip movement in addition to jaw and tongue compensatory movements when the jaw was perturbed during the utterance /ædæ/, which does not require lip activity. Similarly, Kelso et al. (1984) found increased upper lip EMG activity, for the alveolar fricative, in perturbed productions of /bæz/. Third, compensations are flexible and distributed among articulators involved in a specific task. Thus, when the jaw is loaded in the production of a bilabial stop, responses can occur in the jaw itself and/or in the upper and lower lips (Shaiman, 1989). Fourth, compensations are mostly functional and effective in the sense that the intended goal is normally achieved. For example, Munhall et al. (1994) perturbed the lower lip at the transition from the first vowel to the medial bilabial voiceless stop in the utterance /i'pip/. The system was able to overcome the load, making the intended closure of the vocal tract and increasing the air pressure in the oral cavity: Recordings of oral pressure revealed no differences in pressure between load and control productions.

While the results of these studies clearly indicate that the articulatory system is capable of rapid and functional responses to external loads, what happens to the larynx if the lower lip is mechanically perturbed while it is making the oral closure for a bilabial voiceless consonant? Is the phasing between the lips and the larynx maintained in spite of the load? A few studies have examined this question (e.g., Löfqvist & Gracco, 1991; Saltzman, Löfqvist, Kinsella-Shaw, Rubin, & Kay, 1992). Munhall et al. (1994) and Saltzman, Löfqvist, Kinsella-Shaw, Kay, and Rubin (this volume) examined laryngeal responses to lower lip perturbations during the production of a voiceless bilabial stop. In addition to lip and jaw actions to achieve the spatial target of a labial closure, a laryngeal response was evident in the perturbed trials by a delay of the onset of glottal abduction, measured relative to the acoustic onset of the preceding vowel. This delay was presumably made to maintain lip-larynx coordination at the transition from the vowel to the voiceless stop, and resulted in an increased acoustic duration of the preceding vowel. However, the period of bilabial closure for the stop was shortened by the perturbation, while the laryngeal abduction-adduction movement increased in duration. Consequently, the normal phasing between the oral and laryngeal movements was disrupted at the release of the oral closure. As a result, Voice Onset Time increased in the perturbed trials since it depends in part, as we have seen, on the timing between the oral and laryngeal events in stop production. These results suggest that interarticulator timing may be more affected by perturbations than spatial targets such as a closure or constriction in the vocal tract.

SUMMARY

The experimental material reviewed in this paper provides evidence that all the parts of the vocal tract involved in the production of a specific sound are controlled as a unit. In the case of the voiceless consonants discussed here, the laryngeal and oral movements necessary for their production are tightly linked. When one part of the articulatory system is perturbed, the movements of the other parts of the system are flexibly adjusted to attain the spatial goal of closing or constricting the vocal tract, while interarticulator timing may be affected by the perturbation. Under variations in speaking rate, the oral and laryngeal events change together, although they do not scale proportionally. An important task for speech motor control is to define the metric that governs temporal relations among speech movements.

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REFERENCES

Abbs, J., & Gracco, V. L. (1984). Control of complex motor gestures: Orofacial muscle responses to load perturbations during speech. *Journal of Neurophysiology, 51,* 705-723.

Abbs, J., Gracco, V. L., & Cole, K. (1984). Control of multimovement coordination: Sensorimotor mechanisms in speech motor programming. *Journal of Motor Behavior, 16,* 195-232.

Abramson, A. S. (1977). Laryngeal timing in consonant distinctions. *Phonetica, 34,* 295-303.

Dart, S. (1987). An aerodynamic study of Korean stop consonants: Measurements and modeling. *Journal of the Acoustical Society of America, 81,* 138-147.

Dixit, P. (1989). Glottal gestures in Hindi plosives. *Journal of Phonetics, 17,* 213-237.

Folkins, J., & Abbs, J. (1975). Lip and jaw motor control during speech: Responses to resistive loading of the jaw. *Journal of Speech and Hearing Research, 18,* 207-220.

Folkins, J., & Zimmermann, G. (1982). Lip and jaw interaction during speech: Responses to perturbation of lower-lip movement prior to bilabial closure. *Journal of the Acoustical Society of America, 71,* 1225-1233.

Gentner, D. (1987). Timing of skilled movements: Test of the proportional duration model. *Psychological Review, 94,* 255-276.

Gracco, V. L., & Abbs, J. (1985). Dynamic control of the perioral system during speech: Kinematic analyses of autogenic and nonautogenic sensorimotor processes. *Journal of Neurophysiology, 54,* 418-432.

Gracco, V. L., & Abbs, J. (1988). Central patterning of speech movements. *Experimental Brain Research, 71,* 515-526.

Gracco, V. L., & Abbs, J. (1989). Sensorimotor characteristics of speech motor sequences. *Experimental Brain Research, 75,* 586-598.

Gracco, V. L., & Löfqvist, A. (1994). Speech motor coordination and control: Evidence from lip, jaw, and laryngeal movements. *Journal of Neuroscience, 14,* 6585-6597.

Heuer, H. (1991). Invariant timing in motor-program theory. In J. Fagard & P. Wolfe (Eds.), *The development of timing control and temporal organization in coordinated action* (pp. 37-68). Amsterdam: Elsevier.

Hirose, H., Lee, C. Y., & Ushijima, T. (1974). Laryngeal control in Korean stop production. *Journal of Phonetics, 2,* 145-152.

Kelso, J. A. S., Saltzman, E., & Tuller, B. (1986). The dynamical perspective on speech production: Data and theory. *Journal of Phonetics, 14,* 29-59.

Kelso, J. A. S., Tuller, B., Vatikiotis-Bateson, E., & Fowler, C. (1984). Functionally specific articulatory cooperation following jaw perturbations during speech: Evidence for coordinative structures. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 812-832.

Kollia, B., Gracco, V. L., & Harris, K. S. (1992). Functional organization of velar movements following jaw perturbation. *Journal of the Acoustical Society of America, 91,* 2474. (A)

Lisker, L., & Abramson, A. S. (1964). A cross-language study of voicing in initial stops: Acoustic measurements. *Word, 20,* 384-422.

Lubker, J. (1986). Articulatory timing and the concept of phase. *Journal of Phonetics, 14,* 133-137.

Löfqvist, A. (1980). Interarticulator programming in stop production. *Journal of Phonetics, 8,* 475-490.

Löfqvist, A. (1991). Proportional timing in speech motor control. *Journal of Phonetics, 19,* 343-350.

Löfqvist, A. (1992). Acoustic and aerodynamic effects of interarticulator timing in voiceless consonants. *Language and Speech, 35,* 15-28.

Löfqvist, A., Baer, T., McGarr, N. S., & Seider Story, R. (1989). The cricothyroid muscle in voicing control. *Journal of the Acoustical Society of America, 85,* 234-239.

Löfqvist, A., & Gracco, V. L. (1991). Discrete and continuous modes in speech motor control. Papers from the symposium Current phonetics research paradigms: Implications for speech motor control. *PERILUS, XIV,* 27-34. Stockholm: Institute of Linguistics.

Löfqvist, A., McGarr, N. S., & Honda, J. (1984). Laryngeal muscles and articulatory control. *Journal of the Acoustical Society of America, 76,* 951-954.

Löfqvist, A., & McGowan, R. S. (1992). Influence of consonantal environment on voice source aerodynamics. *Journal of Phonetics, 20,* 93-110.

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.

Löfqvist, A., & Yoshioka, H. (1984). Intrasegmental timing: Laryngeal-oral coordination in voiceless consonant production. *Speech Communication, 3,* 279-289.

Munhall, K., Löfqvist, A., & Kelso, J. A. S. (1994). Lip-larynx coordination in speech: Effects of mechanical perturbations to the lower lip. *Journal of the Acoustical Society of America, 95,* 3605-3616.

Munhall, K., & Ostry, D. (1983). Ultrasonic measurements of laryngeal kinematics. In I. Titze & R. Scherer (Eds.), *Vocal fold physiology: Biomechanics, acoustics, and phonatory control* (pp. 145-161). Denver: The Denver Center for the Performing Arts.

Nashner, L., & McCollum, G. (1985). The organization of human postural movements: A formal basis and experimental synthesis. *Behavioral and Brain Sciences, 8,* 135-172.

Newsom Davis, J., & Sears, T. A. (1970). The proprioceptive reflex control of the intercostal muscles during their voluntary activation. *Journal of Physiology, 209,* 711-738.

Nittrouer, S. (1991). Phase relations of jaw and tongue tip movements in the production of VCV utterances. *Journal of the Acoustical Society of America, 90,* 1806-1815.

Nittrouer, S., Munhall, K., Kelso, J. A. S., Tuller, B., & Harris, K. S. (1988). Patterns of interarticulator phasing and their relation to linguistic structure. *Journal of the Acoustical Society of America, 84,* 1653-1661.

Pétursson, M. (1976a). Jointure au niveau glottal. *Phonetica, 35,* 65-85.

Pétursson, M. (1976b). Aspiration et activité glottal. Examen experimental à partir des consonnes islandaises. *Phonetica, 33,* 169-198.

Rothwell, J., Traub, M., & Marsden, C. (1982). Automatic and 'voluntary' responses compensating for disturbances of human thumb movements. *Brain Research, 248,* 33-41.

Saltzman, E., Löfqvist, A., Kinsella-Shaw, J., Rubin, P., & Kay, B. (1992). A perturbation study of lip-larynx coordination. In J. Ohala, T. Neary, B. Derwing, M. Hodge, & G. Wiebe (Eds.), *ICSLIP 92 Proceedings, Addendum* (pp. 19-22). Edmonton: The University of Alberta.

Schmidt, R. (1975). A schema theory for discrete motor skill learning. *Psychological Review, 82,* 225-260.

Shaiman, S. (1989). Kinematic and electromyographic responses to perturbation of the jaw. *Journal of the Acoustical Society of America, 86,* 78-88.

Shaiman, S., & Abbs, J. (1987). Sensorimotor contributions to the temporal coordination of oral and laryngeal movements. *SMLC Preprints* (Speech Motor Control Laboratories, University of Madison) *Spring-Summer 1987,* 185-202.

Shapiro, D., Zernicke, R., Gregor, R., & Diestel, J. (1981). Evidence for generalized motor programs using gait pattern analysis. *Journal of Motor Behavior, 13,* 33-47.

Sock, R., Ollila, L., Delattre, C., Zilliox, C., & Zohair, L. (1988). Patrons de phases dans le cycle acoustique de détente en français. *Journal Acoustique, 1,* 339-345.

Terzuolo, C., & Viviani, P. (1979). The central representation of learned motor patterns. In R. Talbot & D. Humphrey (Eds.), *Posture and movement* (pp. 113-121). New York: Raven Press.

Traub, M., Rothwell, J., & Marsden, C. (1980). A grab reflex in the human hand. *Brain, 103,* 869-884.

Tuller, B., & Kelso, J. A. S. (1984). The timing of articulatory gestures: Evidence for relational invariants. *Journal of the Acoustical Society of America, 76,* 1030-1036.

Viviani, P., & Terzuolo, C. (1980). Space-time invariance in learned motor skills. In G. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 525-533). Amsterdam: North-Holland.

Wann, J., & Nimmo-Smith, I. (1990). Evidence against the relative invariance of timing in handwriting. *Quarterly Journal of Experimental Psychology, 42A,* 105-119.

Wright, C. (1990). Generalized motor programs: Reexamination of claims of effector independence in writing. In M. Jeannerod (Ed.), *Attention and performance XIII* (pp. 294-320). Hillsdale: Lawrence Erlbaum.

Yoshioka, H., Löfqvist, A., & Collier, R. (1982). Laryngeal adjustments in Dutch voiceless obstruent production. *Annual Bulletin* (Research Institute of Logopedics and Phoniatrics, University of Tokyo), *16,* 27-35.

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.