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INTRASEGMENTAL TIMING: LARYNGEAL-ORAL COORDINATION IN VOICELESS CONSONANT PRODUCTION

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Abstract. Recent studies of articulatory timing in speech indicate that the relative timing of articulatory gestures may remain constant across changes in stress and speaking rate. Evidence for this kind of temporal invariance has been shown in studies of oral articulators, mostly for gestures associated with adjacent segments in the speech chain. The present study deals with the same problem at the intrasegmental level, i.e., temporal relations between articulatory events within one segment. Temporal coordination of laryngeal and oral articulations in voiceless consonant production was investigated using transillumination and palatography. Voiceless dental stops and fricatives under different stress conditions spoken at two different rates served as the linguistic material. Two speakers of American English participated. Results suggest that temporal ratios between oral and laryngeal gestures tend to remain constant across changes in stress and speaking rate. These findings are consistent with those obtained for other aspects of speech motor control as well as for other types of human motor behavior, suggesting common modes of control.

Zusammenfassung. Neuere Untersuchungen zur zeitlichen Strukturierung des Artikulationsvorgangs zeigen, daß die zeitliche Aussteuerung zweier Artikulationsvorgänge trotz Änderung von Akzent und Sprechgeschwindigkeit konstant sein kann. Beispiele solcherart zeitlicher Invarianz sind für die oralen Artikulatoren vornehmlich bei der Produktion benachbarter Segmente in fortlaufender Rede aufgezeigt worden. In dem hier vorgelegten Beitrag wird die Frage nach der zeitlichen Koordination auf intrasegmentaler Ebene, d.h. in bezug auf zeitliche Abläufe von Bewegungen der Artikulatoren innerhalb eines Segments, aufgegriffen. Die zeitliche Abstimmung der laryngealen Bewegungsmuster wurde mit der oralen Artikulatoren während der Produktion stimmloser Konsonanten mittels photoelektrischer Glottographie und Palatographie untersucht. Das Untersuchungsmaterial bestand aus dentalen Verschluslauten und Spiranten, welche mit zwei verschiedenen Geschwindigkeiten gesprochen wurden. Versuchspersonen waren zwei Sprecher des Amerikanischen. Es zeigte sich, daß das zeitliche Verhältnis von oralen zu laryngealen Bewegungsabläufen bei Änderung von Akzent und Sprechgeschwindigkeit konstant bleibt. Unsere Resultate decken sich mit Ergebnissen aus Untersuchungen, die sich mit anderen Aspekten der Sprachmotorik und des allgemeinen motorischen Verhaltens befassen. Die Unterstellung gemeinsamer Steuermodi ist naheliegend.

Résumé. Des travaux récents sur la production de la parole montrent que les relations temporelles relative entre gestes articulatoires peuvent rester constantes en dépit des variations d'accent et de vitesse. La plupart de ces résultats ont été obtenus pour des articulations orales et essentiellement pour l'articulation de segments adjacents dans la chaîne parlée. Le travail que nous présentons concerne la coordination temporelle sur le plan segmental, c'est-à-dire les relations temporelles entre les articulations associées à un seul segment linguistique. Les articulations laryngées et orales pour des consonnes non-voisées sont étudiées à l'aide de la photoglottographie et la palatographie. Des occlusives et des fricatives dentales produites à deux vitesses différentes forment le corpus linguistique. Deux locuteurs anglo-américains ont participé à l'expérience, les résultats montrent que les rapports temporels entre les gestes laryngés et oraux restent stables en dépit des variations d'accent et de vitesse. Ces résultats sont en accord avec ceux obtenus pour d'autres aspects de la production de la parole et pour d'autres types de mouvements coordonnés. On peut en conclure qu'il y a des modes de contrôle communs.

Keywords. Articulatory timing, speech production, stress and rate changes in speech, voiceless consonants, laryngeal - oral coordination.

1. Introduction

It is well known that changes in stress and speaking rate can affect the amplitude, velocity and duration of articulatory movements (e.g., [9, 20, 21, 22, 23]). For example, segment durations are usually shorter in unstressed than in stressed syllables, and in syllables spoken at a fast rate. Even though the temporal aspects of individual gestures thus change as a result of stress and rate variations, there is accumulating evidence that the relative timing of different gestures may remain constant across such changes. This evidence has been obtained in several studies of articulatory kinematics.

Kent and Netsell [18], using cinefluorography, found that the amount of articulatory overlap between lip and tongue movements for the syllable /wi/ was relatively insensitive to variations in stress. Kent and Moll [17] investigated consonant clusters beginning with /sp-/ and found that closure for /p/ and release of the constriction for /s/ tended to coincide. Gay [8] noted that the closing movements of tongue body, jaw, and primary articulator from the first vowel to the stop in a sequence of vowel-stop-vowel started simultaneously. Kent, Carney, and Severeid [16] further observed that the relative timing of velar lowering and raising in relation to other articulatory events remained constant across two different speaking rates.

Recently, Tuller, Kelso, and Harris [38] have shown evidence of constant relative timing at the neuromuscular level. Using EMG, they studied phase relationships between muscles controlling the lips, the tongue, and the jaw during CVCVC sequences. Their results showed that the relative timing of onset of muscle activity for lip, tongue, and jaw movements (orbicularis oris, genioglossus, lateral pterygoid, and digastric muscles) associated with vowels and consonant in VCV sequences remained unchanged across variations in both stress and speaking rate. While relative timing patterns did not change appreciably, the duration and amplitude of the EMG signal for a particular gesture varied as a result of the stress and rate changes. These electromyographic results have also been substantiated in records of articulatory movements [13,39].

Examples of constant absolute timing have also been given in recent investigations of speech articulation. In particular, it has been argued that coar-

tication of lip rounding is restricted to a fixed temporal window before a rounded vowel [4, 5]. In these studies, the onset of the rounding gesture started within a relatively fixed temporal interval before the acoustic onset of the rounded vowel. We should recall, however, that the results reported by Lubker [24] for coarticulation of lip rounding in Swedish do not agree with the idea of a fixed temporal window. In this study, onset of lip rounding tended to precede the onset of a rounded vowel in proportion to the duration of the (non-labial) consonant string preceding it.

Production of voiceless stops and fricatives requires simultaneous activity at both the laryngeal and supralaryngeal levels. The timing of these gestures thus provides an interesting field for studies of motor coordination in speech. We have shown previously [28] (see also [30]) that some aspects of laryngeal and oral articulatory events in voiceless consonant production may be temporally locked. In particular, peak velocity of the laryngeal abduction gesture was found to occur at a stable interval from the offset of a preceding vowel irrespective of variations in size, speed, duration and timing of the gesture.

Most studies of relative timing in speech have been concerned with articulatory events for adjacent segments in the speech chain (cf., [3]). The present experiment was therefore designed to explore the problem of interarticulator timing at the intrasegmental level. A further motivation for this study was the uncertainty surrounding current work on coarticulation of lip rounding. Here, language and speaker-specific effects may occur (cf., [25]) implying that the degree and amount of coarticulation can show continuous variations among speakers. Studies of speech timing based on coarticulatory phenomena may thus be inherently variable. In the present experiment, we examine cases of interarticulator timing where the timing is an integral and essential part of the articulatory act. These cases are laryngeal-oral coordination in American English voiceless consonant production across changes in stress and speaking rate.

2. Method

2.1. Procedure

Laryngeal activity was monitored by transillumination [34]. A flexible fiberscope inserted through the nose and held in position by a headband provided illumination of the larynx. The amount of light passing through the glottis was sensed by a photo-transistor placed on the surface of the neck just below the cricoid cartilage and coupled to the skin through a light-tight enclosure. The transillumination signal was recorded on one channel of an FM tape recorder. During the recording session, the view of the larynx was monitored through the fiberscope in order to detect movements and fogging of the lens.

Temporal information on laryngeal articulatory movements obtained by transillumination has been shown to be practically identical to similar information obtained by fiberoptic filming of the larynx [27,42]. Also, comparisons between transillumination and high-speed films have shown good agreement [2]. Transillumination is thus an excellent tool for studying laryngeal behavior in speech. It has better temporal resolution than fiberoptic filming and video recording. Data collection and processing are quick and easy, and larger amounts of material can be handled than with other methods available for laryngeal investigations.

Temporal patterns of oral articulations (tongue-palate contact) were recorded using a custom made artificial palate with implanted electrodes (cf., [19]). Six electrodes at the alveolar ridge were connected in parallel; a battery and a resistor were connected in series between the six electrodes and a reference electrode. Onset and offset of tongue-palate contact could then be identified as changes in the voltage across the resistor, and these changes were recorded on another channel of the tape recorder.

Conventional acoustic recordings were obtained simultaneously using a direction-sensitive microphone. The voice signal was recorded in direct mode on the tape recorder.

A general problem in studies of speech physiology is that of defining measurements that are relevant from the point of view of motor control. The making and the breaking of the oral constriction in obstruents are controlled by muscular forces and were chosen as reference points. Measures of closure and constriction duration were made from the palatographic signal, and the interval between onset and offset of tongue-palate contact was measured, cf., Fig. 1.

For laryngeal articulation, the occurrence of peak glottal opening served as the reference point. This point marks the end of the abduction and the beginning of the adduction of the vocal folds and is under motor control. EMG recordings from intrinsic

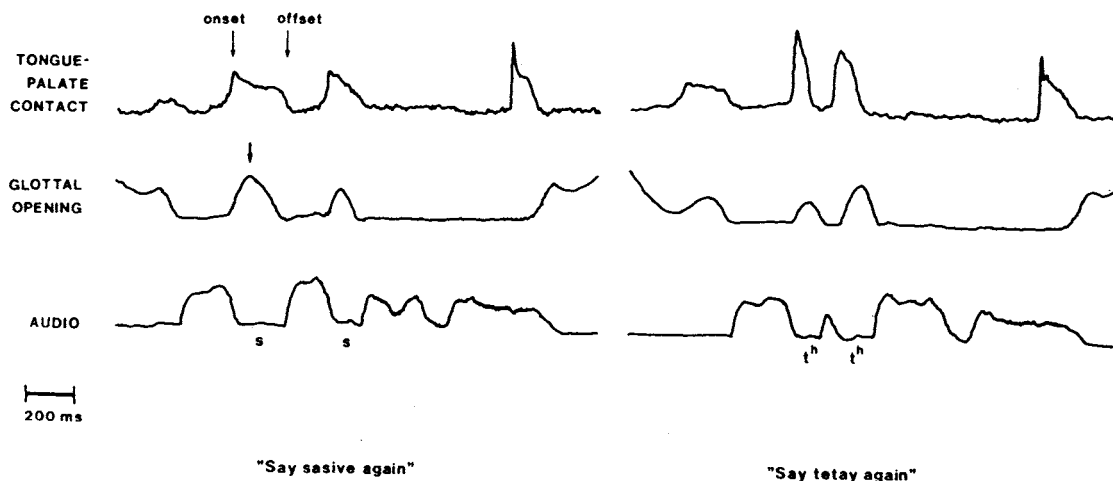


Fig. 1. Sample records of tongue-palate contact signal, transillumination signal, and rectified and integrated audio signal during production of the utterances "Say sasive again" (left) and "Say tetay again" (right). Onset and offset of tongue-palate contact for the initial dental fricative in "sasive" are indicated; arrow at transillumination signal points at peak glottal opening.

laryngeal muscles have indicated a reciprocal pattern of activation for the posterior cricoarytenoid and the interarytenoid muscles in the control of glottal opening in single voiceless consonants (cf., [14,15,27]). This justifies the use of peak glottal opening as a reference in studies of laryngeal articulation in speech.

Measures of interarticulator timing were defined in two ways. First, the interval from onset of tongue-palate contact to peak glottal opening was calculated. This measurement provides an estimate of the relationship between onset of constriction or closure and the beginning of the adduction of the vocal folds. It is useful since it highlights differences in timing between obstruents, e.g., stops and fricatives [28]. A second measurement of interarticulator timing was the interval from peak glottal opening to offset of tongue-palate contact. This measure shows the relationship between onset of glottal adduction and release, and is particularly useful in examining timing differences between different stop categories [26]. The physiological measurements were supplemented by acoustic measurements of voice onset time for stops. All measurements were made interactively on a computer.

2.2. Linguistic material

The linguistic material consisted of nonsense words with dental voiceless stops and fricatives in different positions and under different stress conditions. Transillumination requires a free passage for the light in the pharynx which motivates the use of nonsense words with front vowels. The choice of dental consonants was also motivated by the experimental design. The stress pattern of the nonsense words followed that of regular English words. The

test words are listed in Table 1 together with regular English words having corresponding stress patterns.

Two native speakers of American English, one female and one male, served as subjects. The number of subjects was limited by the requirement of custom making the artificial palate for each subject. The subjects read the material from randomized lists with the test words embedded in a short carrier phrase. First, they read the material at a comfortable speaking rate and then repeated the material at a faster rate. No attempt was made to strictly control the speaking rate; each subject chose her/his own preferred rate. The only requirement was that the two rates should differ from each other. Ten to 15 repetitions of each test word were obtained for each speaking rate.

The stops occurring after a stressed vowel were produced as voiced flaps by both speakers and were not included in the measurements. Speaker 2 also produced the third /t/ in "tatetive" and the second /t/ in "tetetative" as flaps, and these productions were not measured.

3. Results

3.1. Absolute timing

In order to study the effects of stress and speaking rate on the articulatory intervals defined above, a separate analysis of variance was carried out for each speaker. For this analysis, segments were classified as stressed and unstressed, respectively. In this classification, all stops and fricatives occurring in a syllable carrying primary stress were considered to be stressed; obstruents in all syllables not carrying primary stress were classified as unstressed. For example, in the word "sesasive" the second /s/ would be considered stressed whereas the first and third /s/ would be unstressed.

Fig. 2 summarizes the results for the two speakers. This figure shows the duration of the oral constriction or occlusion as well as the occurrence of peak glottal opening during the constriction/occlusion; the latter is indicated by the arrow.

From Fig. 2 it is evident that both stress and rate affect most articulatory intervals under investigation. With one exception to be discussed below, the statistical analysis showed that the effects of stress

Table 1

The linguistic material. The rightmost column lists English words with stress patterns corresponding to those of the test words

| Stop | Fricative | Stress pattern |
|-------------|-------------|----------------|
| 'tative | 'sasive | native |
| 'tatetive | 'sasesive | tentative |
| te'tay | se'say | today |
| te'tative | se'sasive | permissive |
| tete'tative | sese'sasive | radioactive |

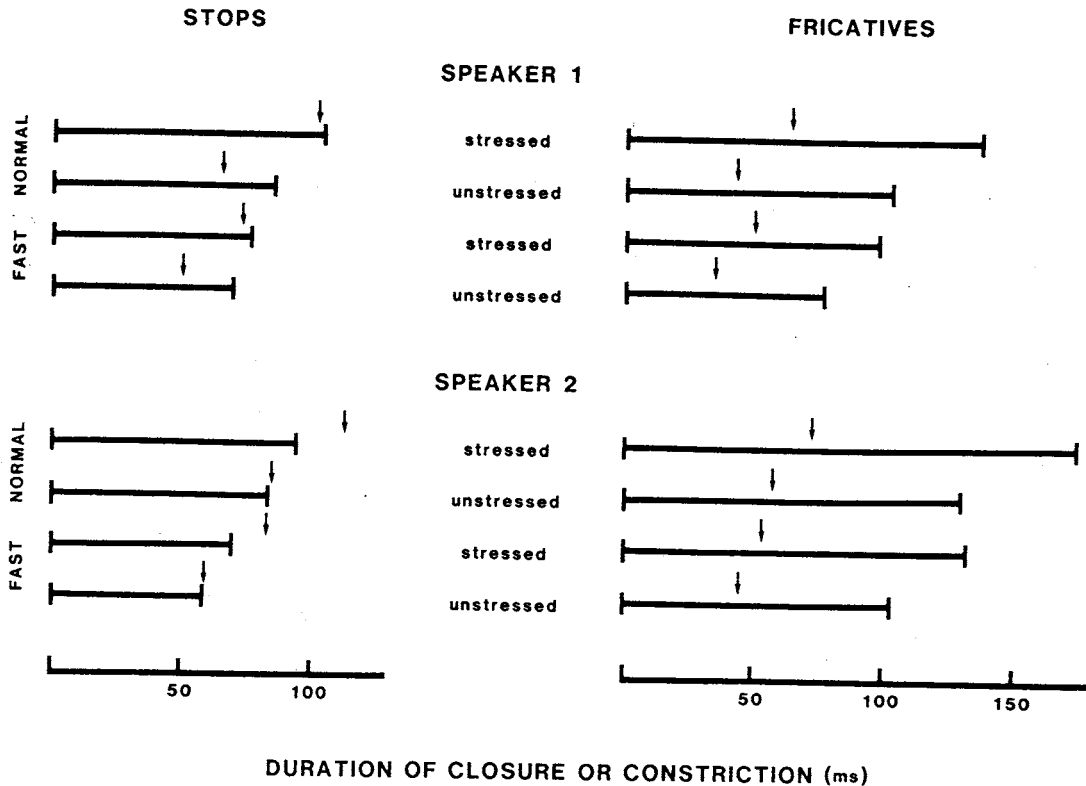


Fig. 2. Summary of articulatory measurements of stops (left) and fricatives (right) for the productions of speaker 1 (top) and speaker 2 (bottom). The lines indicate duration of tongue-palate contact during stop closure and fricative constriction; arrow indicates the occurrence of peak glottal opening.

and rate were highly significant ($p < 0.001$).

Closure duration for stops is generally shorter than constriction duration for fricatives. Both closure and constriction are shorter in unstressed than in stressed segments and also in segments spoken at a faster rate. The change due to stress is somewhat larger for fricatives than for stops in both absolute, about 30 and 15 ms, respectively, and relative terms, 20–25% compared to 10–15%. Also the rate variation causes a slightly greater absolute change in fricative constriction than in stop closure, 30 and 25 ms, but the percentage change is about the same, 20–25%.

The interval from onset of tongue-palate contact to peak glottal opening is shorter in fricatives than in stops. Also for this interval, the influence of stress and rate is similar in that the interval is longer in stressed segments and in segments spoken at a slower rate. The change in this interval due to stress and rate is somewhat larger for stops than for frica-

tives in both absolute and relative terms, 25 and 15 ms, and 30–35% versus 20–25% for stops and fricatives, respectively.

The interval from peak glottal opening to release of tongue palate contact is considerably longer in fricatives than in stops. For the stops, peak glottal opening tends to occur around the release of the oral closure. However, each speaker differed with respect to this parameter. For speaker 1, peak glottal opening usually occurred slightly before the release. For speaker 2, on the other hand, onset of glottal adduction started after the oral release. Speaking rate had a non-significant effect on this interval in stop consonants whereas the effect of stress was highly significant. For speaker 1, peak glottal opening occurs closer to the release in stressed than in unstressed stops. For speaker 2, peak glottal opening is timed to occur later with respect to the oral release in stressed than in unstressed stops.

In the fricative productions, the interval from

peak glottal opening to release of tongue-palate contact is longer in stressed than in unstressed syllables and also longer in slower speech.

3.2. Relative timing

We now turn to a discussion of the effects of stress and rate on relative articulatory timing. Fig. 3 shows a plot of closure/constriction duration against the interval from onset of tongue-palate contact to peak glottal opening for the productions of speaker 1. Each data point represents the mean value for a given obstruent occurring in a particular position in a given word. The figure also presents the Pearson product moment correlations as well as the results of regression analyses. For both stops and fricatives, there is a positive correlation between the two articulatory intervals. The slope of the linear regression fitted to the data is higher for the stops than for the fricatives. This difference in the slope was highly significant at the normal rate, $F(1,22) = 21.46$ ($p < 0.001$), but not significant at the fast rate, $F(1,22) = 2.57$ ($p > 0.25$).

Qualitatively, the slope of the regression lines is

positive at either rate and the data points for the normal and the fast rate form a continuous function. Nor is there any quantitative difference. The difference in slope between rates was not statistically significant, $F(1,18) = 0.05$ and $F(1,26) = 1.54$ for stops and fricatives respectively with $p > 0.1$ in both cases.

The productions of speaker 2 are plotted in the same way in Fig. 4. The overall picture is identical to the one given in Fig. 3. There is the same strong positive correlation between closure/constriction duration and the interval from onset of tongue-palate contact to peak glottal opening for both stops and fricatives. Again, the slope of the linear regression is steeper for the stops than for the fricatives. The difference was highly significant at both rates, $F(1,22) = 131.20$ and $F(1,22) = 16.10$ ($p < 0.001$). The difference in slope between rates was not significant, $F(1,14) = 0.17$ and $F(1,26) = 2.28$ for stops and fricatives, respectively.

Closure/constriction duration is plotted against the interval from peak glottal opening to release for speaker 1 in Fig. 5. We should add, here, that the interval from peak glottal opening to release was

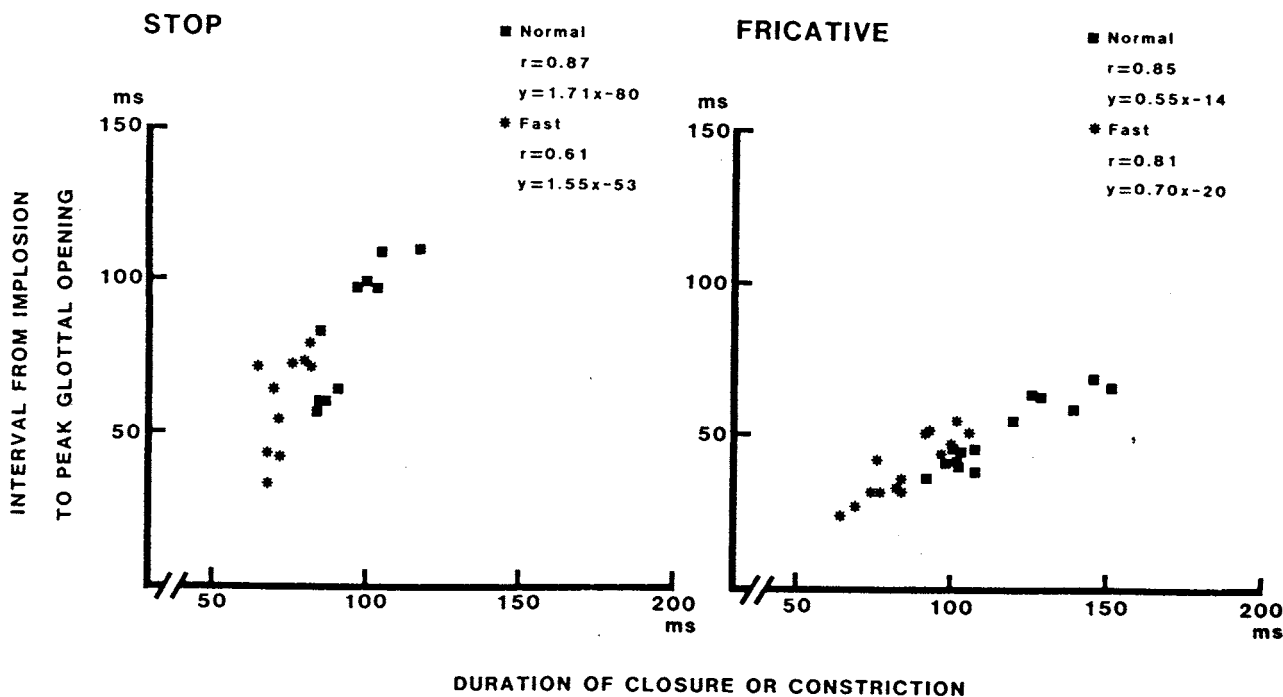


Fig. 3. The interval from implosion (onset of tongue-palate contact), to peak glottal opening plotted against closure/constriction duration for speaker 1.

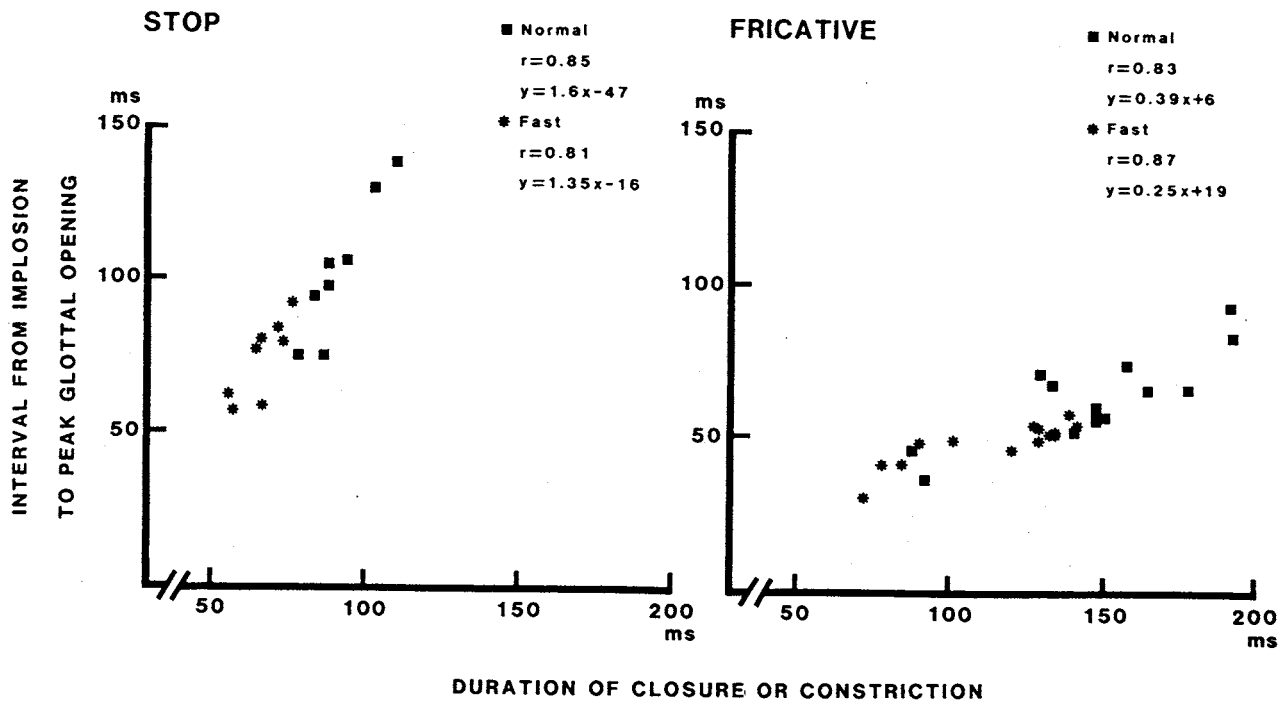


Fig. 4. The interval from implosion (onset of tongue-palate contact), to peak glottal opening plotted against closure/constriction duration for speaker 2.

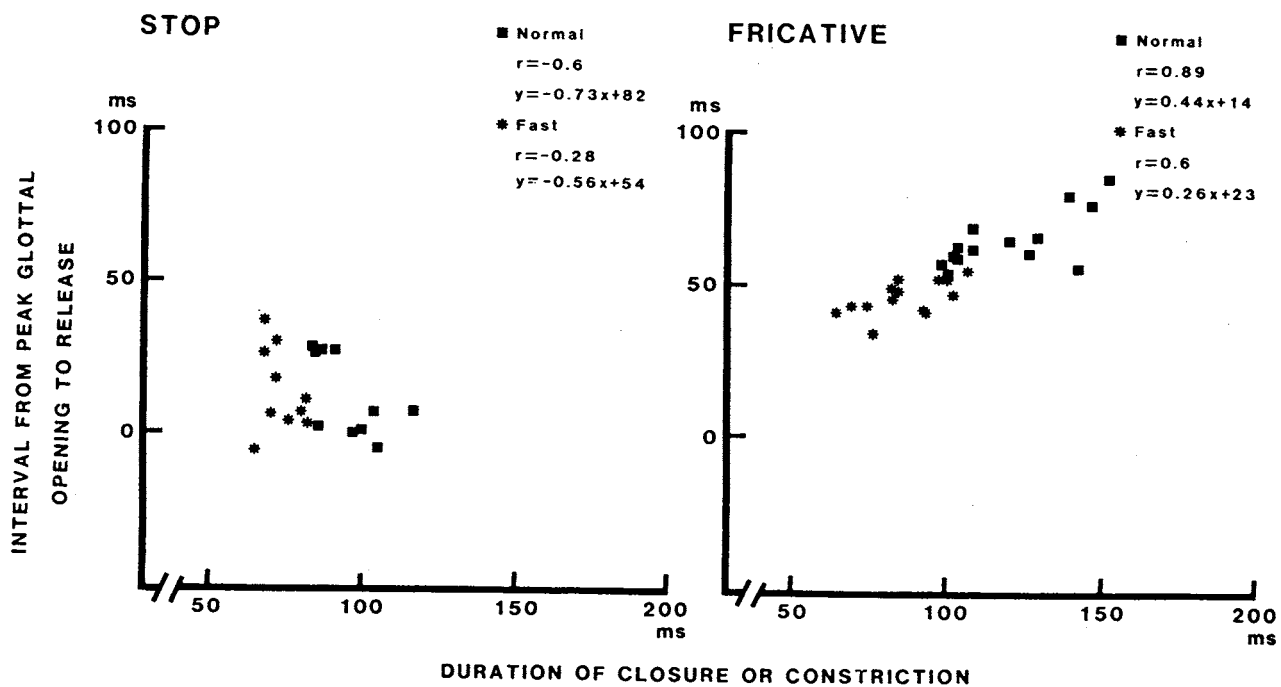


Fig. 5. The interval from peak glottal opening to release plotted against closure/constriction duration for speaker 1.

calculated by subtracting the interval from onset of tongue-palate contact to peak glottal opening from closure/constriction duration. Negative values along the *y*-axis in Fig. 5 thus indicate that peak glottal opening occurred after the release of tongue-palate contact. For the fricatives in Fig. 5, there is a positive correlation between the two parameters. There is, however, a negative correlation for the stop productions. There is no significant difference in the slope of the regression for the fricatives between rates, $F(1,26) = 2.43$.

Fig. 6 plots the duration of closure/constriction against the interval from peak glottal opening to release for the productions of speaker 2. Correlation coefficients are positive for the fricatives and negative for the stops. Again, the difference in slope between rates for the fricatives was not significant, $F(1,26) = 2.15$.

Voice onset time in stop consonants has been shown to depend on the timing of laryngeal and oral articulations. The relationship between the interval from peak glottal opening to release and voice onset time is given in Fig. 7. In all cases, there is a negative correlation between the two parameters. Also, speaker 2 produced longer values of VOT than

speaker 1 which reflects the fact that the generally started glottal adduction after the oral release. At the same time it is evident that voice onset times of different magnitudes can occur with similar values of the interval from peak glottal opening to release. This is the case, in particular, if we compare the two rates. Mean voice onset time for the stressed stops at normal rate was 60 (S.D. 13.6) and 85 (S.D. 10.9) ms for speaker 1 and 2, respectively, and 35 (S.D. 8.7) and 64 (S.D. 7.9) for the fast rate. For the unstressed stops, the same values were 34 (S.D. 13) and 62 (S.D. 10.2) ms at the normal rate, and 16 (S.D. 8.2) and 53 (S.D. 6.5) ms for the fast rate. The difference in voice onset time between rates was significant, whereas the difference in the interval from peak glottal opening to release was not. Hence, this particular measure of interarticulator timing cannot in itself account for the VOT difference between rates.

4. Discussion

The results of the present study suggest that stress and rate variations in general have similar influences

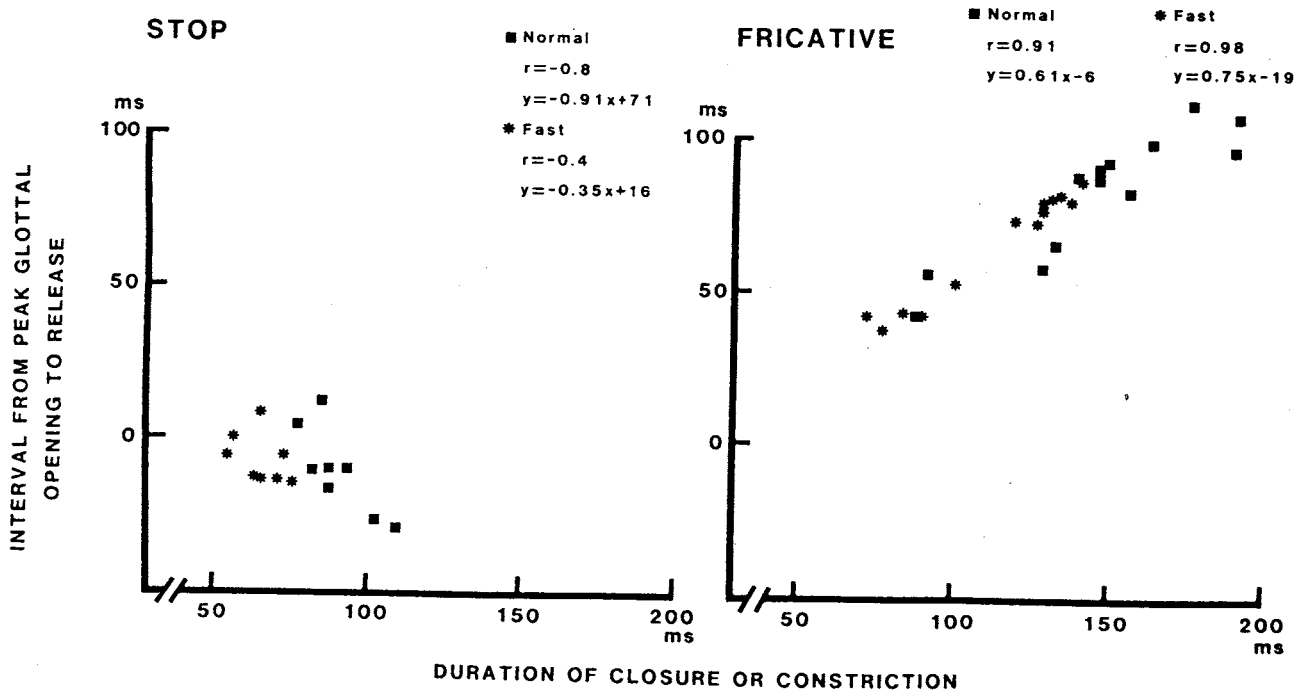


Fig. 6. The interval from peak glottal opening to release plotted against closure/constriction duration for speaker 2.

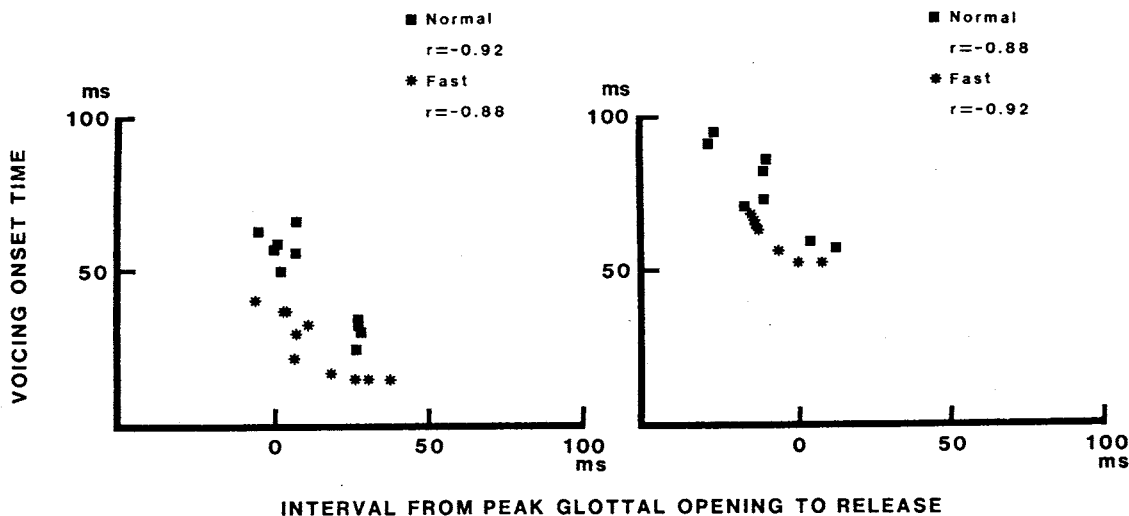


Fig. 7. Voice onset time plotted against the interval from peak glottal opening to release for speaker 1 (left) and speaker 2 (right).

on temporal articulatory parameters in voiceless stop and fricative production. That is, closure/constriction duration is shorter in unstressed than in stressed syllables and also in syllables spoken at a faster rate. Similarly, the absolute duration of articulatory intervals measured across articulators is shorter in unstressed than in stressed syllables.

At the same time, there are certain differences between stops and fricatives, in particular concerning relative articulatory timing. For example, duration of tongue-palate contact for fricative constriction is longer than tongue-palate contact for stop closure, and peak glottal opening consistently occurs closer to onset of fricative constriction than to onset of stop closure.

These, and other articulatory differences between voiceless stops and fricatives are most likely due to different aerodynamic requirements for stop and fricative production. In the present material, all stops are postaspirated. The timing of peak glottal opening, i.e., onset of glottal adduction, close to the oral release will thus ensure a large glottal opening at the release. This results not only in a delay of voice onset but also in favorable aerodynamic conditions for noise generation at the oral place of articulation when the oral passage progressively widens during the release. As the glottis is adducted following the oral release, aspiration noise is generated in the glottis before the periodic vibrations start for the following vowel.

For the fricatives, a rapid increase in glottal opening stops laryngeal vibrations and also contributes to a high rate of air flow through the glottis thus facilitating the generation of friction noise in the oral cavity. We have shown previously that peak glottal opening tends to be larger for fricatives than for stops [28] and that peak velocity of glottal abduction is higher for fricatives than for stops. These differences in laryngeal articulation between voiceless stops and fricatives have been found for several speakers of different and unrelated languages and might thus be universal.

The difference in voice onset time between stressed and unstressed stops is due to the phonology of English. As has been noted (e.g., [1,26,28]) the control of voice onset time is linked to the timing of oral and laryngeal articulations. This is illustrated in Fig. 7, where there is a negative relationship between the interval from peak glottal opening to release and voice onset time. Even though interarticulator timing thus appears to be the basic mechanism for the control of aspiration, the rate effect on voice onset time obviously cannot be accounted for by interarticulator timing alone. Some other factors must also be involved, and in the present context one might assume that differences in glottal opening size occur. An overall smaller glottal opening in the fast rate would explain the VOT difference between rates.

The effects of stress and speaking rate on articulatory parameters in the present study are consis-

tent with those obtained in other investigations (e.g., [20,21,22,23,37]). At the level of interarticulator timing, however, the present results exemplify time-locking of articulatory events across changes in stress and rate. We should add the obvious qualification that this notion of temporal constancy is based on averages and non-significant statistical differences between means.

The temporal relationship between onset of glottal adduction and oral release in voiceless stops appears to be unaffected by variations in rate for stressed and unstressed stops, respectively, cf., Figs. 2 and 7. Constant relative timing occurs between closure duration and the interval from onset of tongue-palate contact to peak glottal opening for both stops and fricatives, cf., Figs. 3 and 4. There is a high positive correlation between these intervals, and the ratio between them thus tends to remain constant across variations in stress and rate.

The present findings of constant relative timing in speech production across metrical changes add to an increasing body of data suggesting that relative timing is a general feature not only of speech motor control but also of control of coordinated movements in general. In motor control, relative timing thus seems to be maintained while amplitude varies. In the motor control literature, this has been noted for locomotion [12,32,33] for handwriting [6,40], and typing [36] (see also [10,11,41]). The speech production data presented in this and other studies [30,37] thus converge with those obtained in investigations of other types of motor activities suggesting a picture where relative timing appears to play a crucial role. While we have examined timing at the intra-segmental level, our results are compatible with those obtained at the intersegmental level, i.e., timing across sequences of linguistic segments [13,38].

Speech production is a goal directed behavior. Speech movements are executed to produce an acoustic signal that can transmit linguistic information. If relative timing is an important part of speech motor control, it is reasonable to assume that traces of relative timing can be found in the acoustic signal, and would thus play a role in the perception of speech. This is indeed the case, as has been shown in several studies of speech perception across variations in speaking rate [7,29,31,35]. The relevance of relative timing is thus well established for both production and perception of speech.

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