Laryngeal adjustments in the production of consonant clusters and geminates in American English

Hirohide Yoshioka

Haskins Laboratories, 270 Crown Street, New Haven, Connecticut 06510 and Research Institute of Logopedics and Phoniatrics, Faculty of Medicine, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, 113 Japan

Anders Löfqvist

Haskins Laboratories, 270 Crown Street, New Haven, Connecticut 06510 and Department of Phonetics, Lund University, Helgonabacken 12, S-223 62 Lund, Sweden

Hajime Hirose

Research Institute of Logopedics and Phoniatrics, Faculty of Medicine, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo, 113 Japan
(Received 15 December 1980; accepted for publication 14 August 1981)

The glottal opening gesture and its timing control in various sequences of voiceless obstruents were investigated by the combined techniques of electromyography, photo-electric glottography, and fiberoptic endoscopy. The results obtained at both electromyographic and movement levels revealed that the glottal opening gesture is characterized by a one-, two-, or more-than-two-peaked pattern in a regular fashion according to the phonetic nature of the voiceless segments: each voiceless obstruent or geminate accompanied by aspiration or frication noise tends to require a single separate peak of the opening gesture, while an unaspirated stop embedded in a voiceless environment can be produced within the opening gesture attributed to an adjacent aspirated stop or fricative. Such an independent opening gesture of the glottis for the production of voiceless aspirated stops or voiceless fricatives even in sequentially unvoiced contexts can be interpreted as assuring the aerodynamic requirements for turbulent noise production during the aspirated stop or fricative segment.

PACS numbers: 43.70.Bk, 43.70.Ve, 43.70.Ny

INTRODUCTION

It has been universally recognized that the larynx plays the major role in accomplishing the phonemic distinction of voicing. Although some issues remain concerning the details of voicing onset and offset as well as the participation of other articulators, the approximation and separation of the vocal folds are considered crucial conditions among other physical and aerodynamic factors determining the initiation, maintenance, and cessation of vocal fold vibrations (e.g., Fant and Scully, 1977). Many studies, using various techniques such as photo-electric glottography and fiberoptic endoscopy, have confirmed that the precise degree and timing of the glottal opening and closing gesture relative to the supraglottal articulatory movements are critically linked to the manifestation of the distinctive feature of voicing, and also aspiration in languages where the presence or degree of aspiration is phonemic (Frøkjaer-Jensen *et al.*, 1971; Kagaya, 1974; Dixit, 1975; Kagaya and Hirose, 1975; Iwata and Hirose, 1976; Pétursson, 1976).

Furthermore, the phonetic variation of aspiration in stop consonant production in English and Swedish has been shown to be based on different time courses of the glottal opening gesture (Lisker *et al.*, 1969; Sawashima, 1970; Lindqvist, 1972; Löfqvist, 1976). As for nondistinctive variations in voicing, the vowel devoicing phenomenon in Japanese, for example, has also been demonstrated to be accompanied by an open glottis, which is chiefly responsible for unvoicing in this particular allophonic variation (Sawashima, 1971). Although the /h/-voicing phenomenon in Japanese, another type of phonetic variation in voicing, cannot be well-explained solely in terms of glottal aperture (Yoshioka, 1979), the dimension of glottal opening and closing has, at least in most voiced versus voiceless pairs, proved to be substantially correlated with quasi-periodic excitation at the glottal level.

The electromyographic work of the past decade has further confirmed that the degree and timing of the glottal opening are controlled, at least in gross terms, by reciprocal activity patterns of the abductor and adductor muscle groups of the larynx (Hirose and Gay, 1972). Although functional differences among adductor muscles have not been well investigated in relation to glottal movements, the activity pattern of the posterior cricoarytenoid muscle, considered to be the sole abductor, has been shown to be most critical for determination of the glottal aperture in general (Hirose, 1976). Thus experiments simultaneously recording both electromyographic and movement parameters have revealed that the contrast of voiced versus voiceless, as well as that of aspirated versus unaspirated, is accounted for in terms of the underlying neuromuscular control of these muscles, except for the /h/-voicing phenomenon in Japanese, mentioned above.

These investigations, however, have dealt mainly with simple speech materials such as the alternating phoneme sequences, /CVCV/, /CVCVC/, or /VCV/ (C = consonant and V = vowel). Such studies have been directed towards the understanding of laryngeal control in voicing distinctions and/or variations under circumstances of minimal mutual interaction between adjacent phones with respect to voicing. Since vowels are usually voiced and most of the consonants in many languages seem to be clearly specified by either a voiced (lax) or a voiceless (tense) feature, and indeed are binary in this sense (e.g., Jakobson *et al.*, 1951), coarticulatory phenomena at the glottal level would not be very likely to appear in these contexts. In this connection, the study of vowel devoicing can be interpreted as aiming at the exceptional cases where laryngeal coarticulation does occur. In contrast, many other coarticulation studies, most of which deal with supralaryngeal articulations, have focused on observing coarticulation during sounds specified as "neutral" with regard to certain features such as lip rounding and nasalization.

In addition to examining laryngeal coarticulation in regularly alternating phoneme combinations, it is also interesting to find out how phoneme sequences homogeneous with respect to voicing are organized at the level of the glottis in terms of their neurophysiological correlates. The present paper is intended to clarify the temporal change of the glottal opening gesture and its neuromuscular control during the production of clusters of voiceless obstruents in American English. We believe that these kinds of studies, focused on sequential voiceless sounds, may provide insight into coarticulatory phenomena at the level of laryngeal adjustments as well as provide additional information on the biomechanical properties of the opening and closing movements of the vocal folds from a kinesiological viewpoint. Another purpose of the study is to explore the phonetic effect, it any, of word boundaries on laryngeal articulation, since some voiceless phonemes and voiceless sequences in American English may occur in a variety of linguistic situations, i.e., they may be preceded, followed, or interrupted by a word boundary.

I. METHOD AND PROCEDURE

The experiment was conducted in two parts; one is an electromyographic (EMG) study of the larynx and the other is a movement study using the combined techniques of photo-electric glottography and fiberoptic endoscopy of the glottis.

The EMG data were obtained using bipolar hooked-wire electrode techniques (Basmajian and Stecko, 1962; Hirano and Ohala, 1969). The electrodes, consisting of a pair of platinum–tungsten alloy wires (50 μ in diameter with isonel coating), were inserted perorally into the posterior cricoarytenoid muscle (PCA) under indirect laryngoscopy with the aid of a specially designed curved probe (Hirose *et al.*, 1971). Before the insertion, topical anaesthetic was applied to the mucous membrane of the hypopharynx using a small amount of 4% lidocaine spray (Xylocaine). The interference voltages of the EMG signals were recorded on an FM multichannel data recorder in parallel with the acoustic signal. These action potentials were then fed into a digital computer system and sampled at a rate of 200/s after being rectified and integrated over a 5-ms time window, for further processing to obtain the muscle activity patterns for single and/or ensemble-averaged tokens (Kewly-Port, 1977). The figures to be presented in this paper represent activity patterns aligned with reference to particular acoustic events, and smoothed with a time constant of 35 ms, before ensemble averaging.

For the movement data, the glottal view through a flexible laryngeal fiberscope (Olympus VF-O type, 4.5 mm in outer diameter) was photographed with a cine camera at a rate of 60 frames/s. Both the audio signal and the synchronization signal were registered on the FM recorder tape to identify each frame. Then, frame-by-frame analyses were made with the aid of a minicomputer to calculate, on each frame, the distance between the vocal processes. The distance is considered as one of the indicators of the glottal width (Sawashima and Hirose, 1968; Sawashima, 1976).

The cold dc light source (Olympus CLS), providing illumination of the upper glottal area, also served as the light source for the photo-electric glottography.[1] The amount of light passing through the glottis was sensed by a photo-transistor (Philips BPX 81) placed on the neck just below the lower edge of the cricoid cartilage. The electrical output of the photo-transistor also was recorded on another channel of the FM tape. These three signals were sampled at 200/s and processed in the digital system; they will be shown with a 5-ms integration-time constant.

A native male speaker of standard American English served as the subject. Among the possible voiceless phoneme sequences in American English, the combination of /s/ and /k/ is optimum in forming the greatest possible number of meaningful contexts. Therefore, as is shown in Table I, "sentences" containing the phonemes /s/ and /k/ in many combinations were selected for the test utterances. The abbreviated phonemic transcriptions indicate the types of clusters with which the experiment is concerned. In the first EMG session, the subject was asked to produce the 24 utterance types, 12 times each, in random order. For the movement study, simultaneous recordings of photo-electric output and fiberoptic cine film were made during the first two repetitions of each utterance type, followed by 12 additional recordings of only the photo-electric signal. During the session, the glottal image was constantly monitored through the fiberoptic view finder. Although no particular instruction was given to the subject about the vocal intensity or the speaking rate, a gross survey of audio waveforms and acoustic envelopes revealed

TABLE I. Test utterance types.

1.	I may aid	/v#v/	13.	I mask aid	/sk#v/
2.	I may sale	/v#s/	14.	I mask sale	/sk#s/
3.	I may cave	/v#k/	15.	I mask cave	/sk#k/
4.	I may scale	/v#sk/	16.	I mask scale	/sk#sk/
5.	I make aid	/k#v/	17.	He makes aid	/ks#v/
6.	I make sale	/k#s/	18.	He makes sale	/ks#s/
7.	I make cave	/k#k/	19.	He makes cave	/ks#k/
8.	I make scale	/k#sk/	20.	He makes scale	/ks#sk/
9.	My ace aids	/s#v/	21.	He masks aid	/sks#v/
10.	My ace sales	/s#s/	22.	He masks sale	/sks#s/
11.	My ace caves	/s#k/	23.	He masks cave	/sks#k/
12.	My ace scales	/s#sk/	24.	He masks scale	/sks#sk/

that the intra-session variability for each utterance type is comparable with that across sessions.

II. RESULTS

Figure 1 contains the glottographic patterns for eight tokens of three utterance types, where the place of the word boundary in the /sk/ sequence varies. In each graph, the vertical dotted line corresponds approximately to the onset of the [s] segment, which served as the line-up point for the sampling and averaging. More specifically, the acoustic reference was determined by identifying the voicing offset for the preceding vowel in the audio waveform of each utterance type. An overall survey of Fig. 1 reveals that, although there are some variations within each utterance type particularly in the peak values for type 11, the glottograms for type 4 and type 13 show one single opening gesture of the glottis for the voiceless segments, while those for type 11 clearly demonstrate two separate opening gestures for the same phoneme sequences.

In order to illustrate the corresponding activity patterns of the abductor muscle (PCA), which is presumably most responsible for the glottal aperture, Fig. 2 shows the averaged electromyographic curves for this muscle for the same three utterance types. In addition, for each utterance type, a representative plot of glottal width as a function of time drawn from fiberoptic data (GWf) is included along with a glottographic curve recorded simultaneously by transillumination (GWt). Also, for both electromyographic and glottal width data, the corresponding audio envelope curves (AE), aligned with reference to the onset of [s], are shown for gross segmentation of the acoustic events.[2] These curves further confirm that the difference in the number of peak openings among the productions of the /sk/ combination is inherently linked to an underlying difference in the activity pattern of the abductor muscle, with some time lead: Two distinct peaks in the PCA activity curve are found for type 11, where a word boundary intervened within the /sk/ sequence, but there is only one peak for the utterance types without the boundary. Note that the PCA activity pattern for the /s # k/ sequence in utterance type 11 shows complete relaxation down to the noise level, preceded by a peak around the line-up and followed by reactivation. The extra small peaks found in the PCA curves for utterance types 11 and 13 correspond to the release of the glottal attack for word-initial vowels in the frame sentences, [ʔe] in "My *ace* caves" and [ʔe] in "I mask *aid*," respectively (Hirose and Gay, 1973).

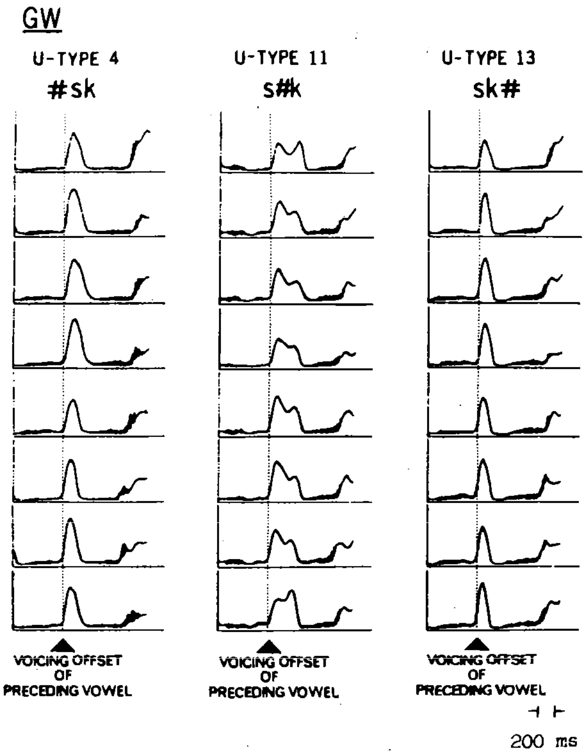

FIG. 1. Glottographic patterns for eight productions of three utterance types containing the /sk/ sequence in various contexts.

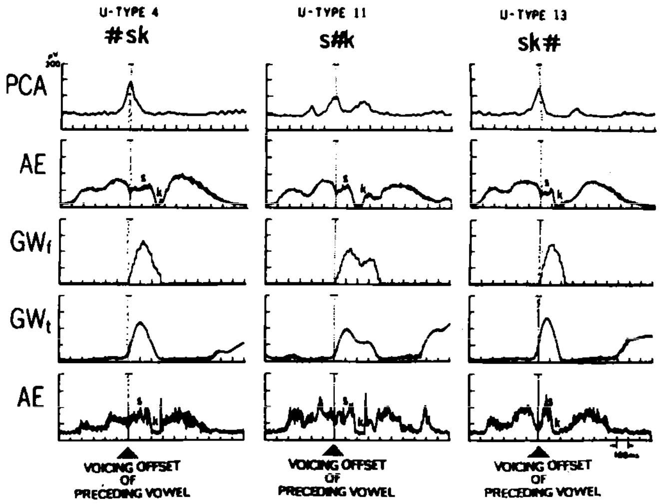

FIG. 2. Averaged electromyograms of PCA, averaged audio envelopes, representative plots of glottal width using fiberoptics, corresponding glottograms, and audio envelopes for the same three utterance types as in Fig. 1.

A closer comparison of the acoustic signals at the bottom, with the corresponding time courses of the glottal width, reveals that the local maximum openings of the glottis are always reached during the fricative segment [s] and aspirated stop [k^h] if any. No specific opening gesture may be detectable for the unaspirated stop [k] in utterance types 4 and 13. Rather, the glottal articulation during this particular allophone seems to be merely a continuation of the closing phase of the glottal gesture for the preceding [s] segment, since the curves are almost symmetrical with regard to their peak timing. The peak glottal openings for utterance types 4 and 13 are quite comparable. The velocity of the glottal movement appears to be a little faster for the word-final /sk/ cluster than for word-initial /sk/ sequence in both opening and closing phases, since the frication duration is usually shorter in word-final position. In contrast, neither of the local maximum values in the glottal width curve for utterance type 11 is as high as those for the other two utterance types. Taken together, the fact that both [s] and [k^h] require certain amounts of glottal opening also means that such a temporary closing

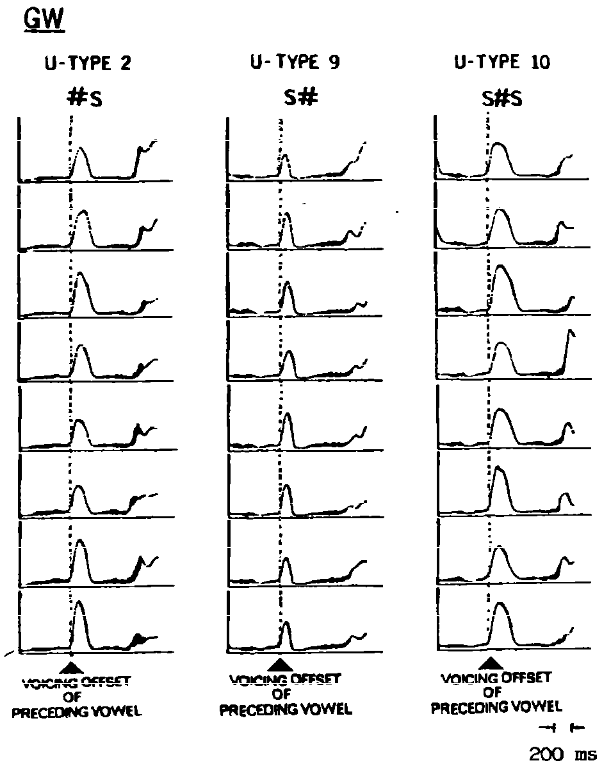

FIG. 3. Glottographic patterns for eight productions of three utterance types containing the fricative /s/ in various contexts.

movement (shown as a dip between peaks in type 11) should not be interpreted simply as the presence of a prolonged pause by the word boundary, but as a controlled narrowing in this particular context.

Figures 3 and 4 compare the productions of the phoneme /s/ in various contexts including a geminate combination. It should be mentioned here that, as is indicated by the acoustic signals, the geminated sound /s # s/ was produced with prolonged continuous frication noise. The averaged abductor activity curves (shown in Fig. 4) as well as the glottographic patterns for the first eight tokens (shown in Fig. 3) among these three utterance types are all characterized by one single opening peak, regardless of the word boundary position. The detailed patterns of the curves, however, differ in several aspects, besides the additional small peaks in the PCA curves, which correlate with the glottal attack of word-initial vowels: The maximum opening for word-final /s/ is generally smaller than that for the work-initial /s/, and the frication period is shorter in final position. Consequently, the velocity of the opening as well as the closing phases does not seem significantly different in either position. Although the movement curves for both cases of /s/ are nearly symmetrical around their peaks, the curve for the geminated case /s # s/ appears to be characterized by slower velocity of its closing phase. In other words, the glottal opening during the geminate sequence reaches its maximum as quickly as during the single ones, but the width decreases slowly until the end of the prolonged frication.

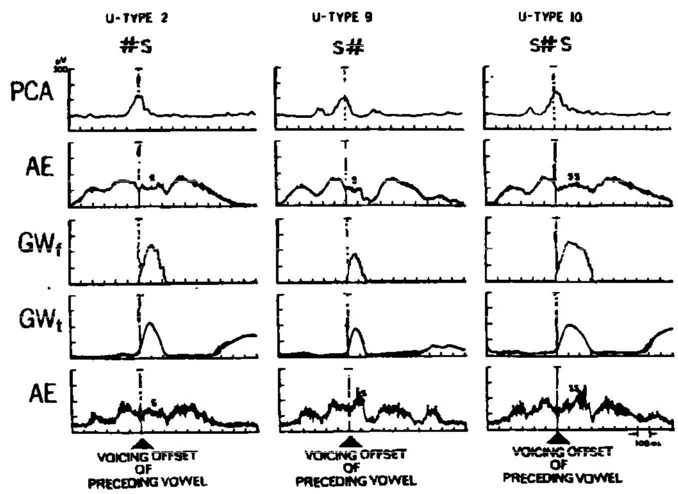

FIG. 4. Averaged electromyograms of PCA, averaged audio envelopes, representative plots of glottal width using fiberoptics, corresponding glottograms, and audio envelopes for the same three utterance types as in Fig. 3.

Figures 5 and 6 illustrate the production of the geminate combination /k # k/ in contrast with the corresponding single voiceless stops. The acoustic signals revealed that the geminated sound was uttered with a longer duration of the closure period followed by a degree of aspiration comparable to that for a single aspirated stop [k^h]. The curve of the abductor activity pattern, as well as those of glottal opening for the geminate, also appears to be characterized by one single peak similar to that for the word-initial aspirated [k^h], although a word boundary intervenes within the geminate. In addition, the stop burst, indicated by

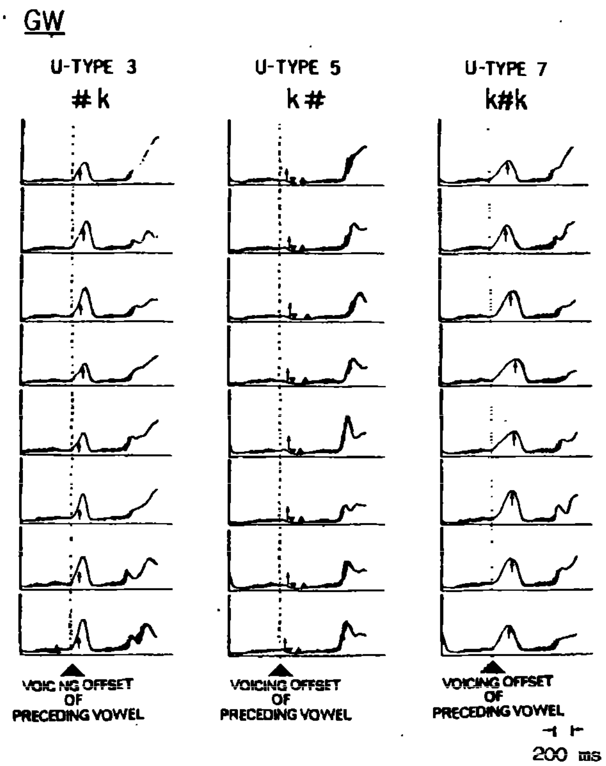

FIG. 5. Glottographic patterns for eight productions of three utterance types containing the stop /k/ in various contexts.

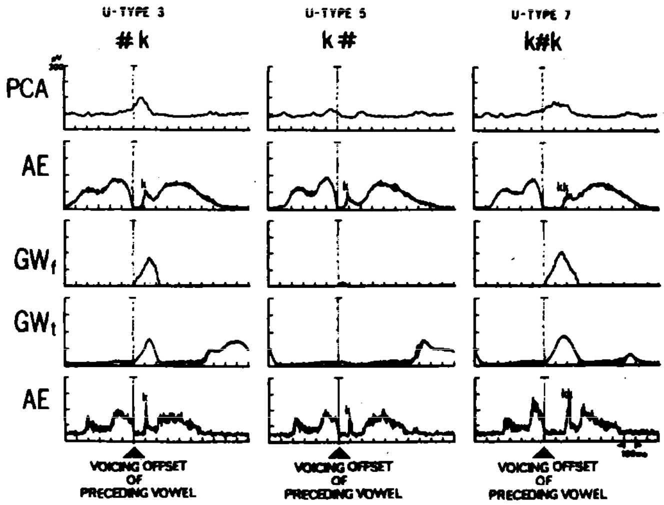

FIG. 6. Averaged electromyograms of PCA, averaged audio envelopes, representative plots of glottal width using fiberoptics, corresponding glottograms, and audio envelopes for the same three utterance types as in Fig. 5.

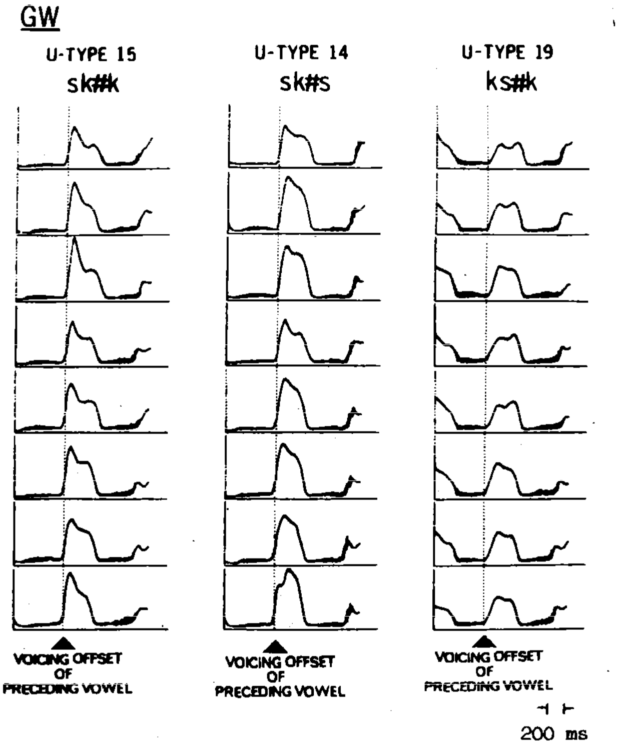

FIG. 7. Glottographic patterns for eight productions of three utterance types containing clusters of three voiceless phones.

arrows in the graphs of Fig. 5, shows that, at least in this subject, the glottal opening is at its maximum during the aspiration period for the single stop, while it peaks before, or around, the burst for the geminate cognate. In contrast, the word-final /k/ is completely different. In the glottographic figures, the pointed triangles at the left in utterance type 5 correspond to the implosion of the stop and those to the right indicate the release for the glottal attack of the following vowel. The data clearly demonstrate that the word-final stop /k/ was actually produced with a negligibly small opening gesture of the glottis, presumably due to glottalization in this position.

Figures 7 and 8 compare three similar three-phone combinations. Although the number of peak openings is not always easy to count, there is a general tendency for each type of voiceless cluster in these utterances to be produced with essentially two separate peaks in the opening gesture both at the electromyographic and the movement levels. Moreover, a gross acoustic segmentation, by inspection of the acoustic envelope, makes it possible to identify the affiliation of each separate opening gesture: The word-initial /s/ and /k/ appear to be produced with a single opening gesture, while the word-final /sk/ and /ks/ are pronounced within another separate opening of the glottis. It is also evident that the local maximum openings are attained during the fricative [s] segment and the aspirated [k^h] segment regardless of utterance type, which is consistent with the previous results for the various /sk/ combinations.

In most of these bimodal glottal opening gestures, the first peak is larger than the second. There are, however, several exceptions to this rule; the averaged PCA curve for utterance type 19 in Fig. 8, the glottogram for the token # 8 of utterance type 14 in Fig. 7, and those for the token # 1, 2, 4, and 5 of utterance type 19 in Fig. 7. Another closer look reveals that the first local maximum value of glottal opening during the word-final /ks/ production of utterance type 19 is smaller than those for the word-final /sk/ sequences of types 14 and 15, despite the fact that peak opening in type 19 usually occurs later than those in types 14 and 15. The small peak opening for the word-final /ks/ sequence in type 19 is, therefore, most likely correlated with the slower velocity of the glottal movement.

Figures 9 and 10 contain three combinations, each composed of four phones. The variability in the number of peaks tends to increase with the number of sequential voiceless phones; therefore we show here

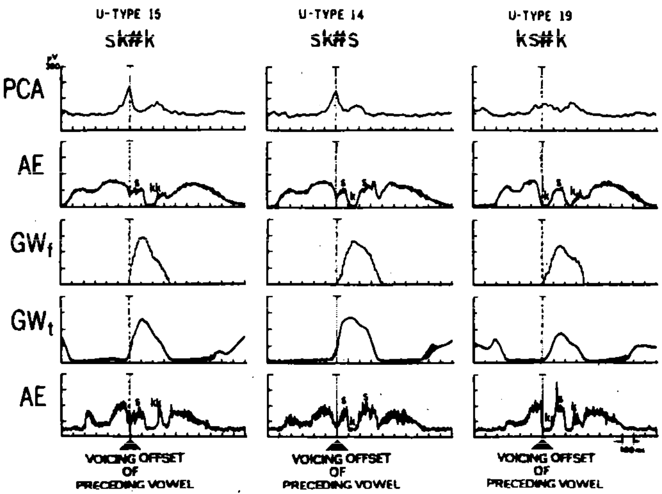

FIG. 8. Averaged electromyograms of PCA, averaged audio envelopes, representative plots of glottal width using fiberoptics, corresponding glottograms, and audio envelopes for the same three utterance types as in Fig. 7.

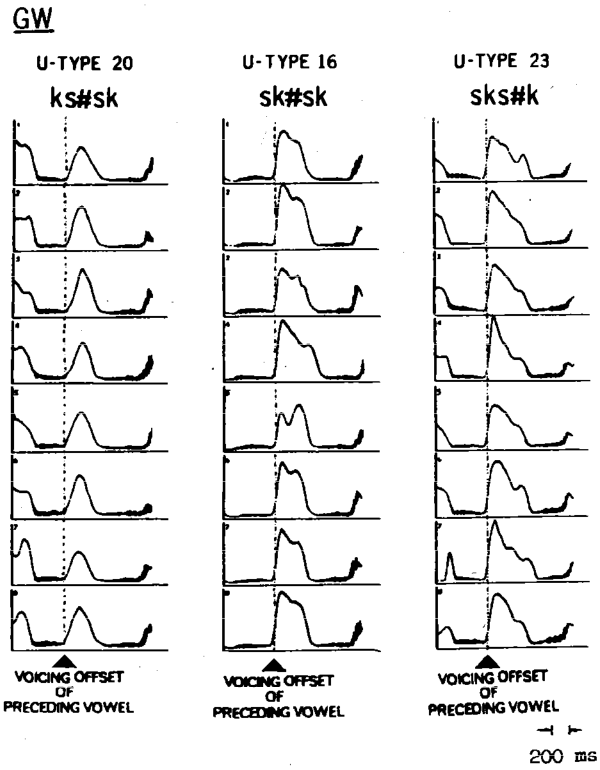

FIG. 9. Glottographic patterns for eight productions of three utterance types containing clusters of four voiceless phones.

the single token patterns of PCA activity in Fig. 10, in addition to those of glottography in Fig. 9. These figures further indicate that each voiceless obstruent or geminate accompanied by aspiration or frication noise

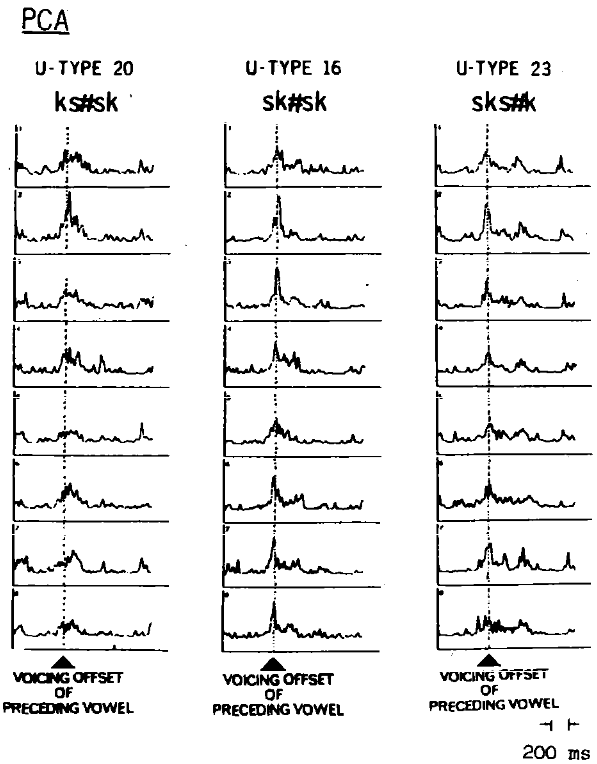

FIG. 10. PCA activity patterns for eight productions of the same three utterance types as in Fig. 9.

tends to require a single separate opening gesture, while an unaspirated stop in a voiceless environment can be produced within the opening gesture attributed to the adjacent aspirated stop or fricative. Thus, both EMG and movement curves of the eight productions for these three utterance types seem to be characterized as one, two, and three peaks, respectively, although identification is complex and uncertain in some cases. Observation of the velocity of the glottographic curves further reveals that the initial opening phase is slower for the voiceless sequence beginning with /k/ in type 20 than those for the clusters beginning with /s/ in types 16 and 23, resulting in a difference between these two groups in the magnitude of the first peak: The local maximum opening for /ks/ in type 20 is generally smaller than for /sk/ in types 16 and 23. These findings are reasonably comparable to those described in Figs. 7 and 8.

III. DISCUSSION

There are a few experimental reports on laryngeal articulation during clusters and/or geminates of voiceless obstruents, but the spoken samples in most are limited. Frøkjaer-Jensen *et al.* (1971) stated that the /s # p/ sequence in Danish subjects showed a two-peaked shape in slower pronunciation but only a single peak in normal speech. Lindqvist (1972) observed glottographic patterns during the Swedish word-initial /sp/ sequence and found that there was no abduction gesture specific to the stop production. Fujimura and Sawashima (1971) described the glottalization of morpheme final [t] in the /t #t/ or /t # d/ sequence in American English in terms of false cord approximation, based on qualitative analysis of fiberoptic filming. From recordings of four Japanese subjects, Sawashima and Niimi (1974) reported that the glottal opening gesture during voiceless segments, including geminates, showed a rather simple pattern with a single peak, together with some individual variations—particularly in the peak values. Their materials did not contain "pure" voiceless clusters due to the fact that the phonology of Japanese does not allow voiceless clusters other than geminates. Löfqvist (1978) presented simultaneous recordings of glottograms and certain aerodynamic parameters during selected Swedish obstruent sequences and demonstrated that the peak glottal opening was found to occur during the fricative in clusters of stop + fricative and fricative + stop. Pétursson (1978) investigated the cluster production in Icelandic, showing the two peaks for [s # t^h], one for [# st].

The current results are generally in good agreement with those data, despite differences in the languages studied and the small subject sample in each study. These findings appear to be correlated with the aerodynamic requirement for obstruent production: A widely open glottis during these segments is indispensable for the egressive air flow that provides the source of aspiration or frication noise (e.g., Stevens, 1971), while this is not necessarily the case for the unaspirated stop.

An overall view of the entire EMG and movement data shows some interesting patterns. Figure 11 shows the relationship between the first local maximum opening of the glottis and the first peak value of the PCA activity during each of the 23 different combinations of voiceless obstruents /s/ and /k/, using the averaged glottographic curves and the averaged EMG activity patterns, respectively. The plotted characters "S" and "K" stand for voiceless sequences beginning with /s/ and /k/, respectively, such as "S" for /sk # k/ and "K" for /ks # k/. That is, the point "K" means that the $X-Y$ coordinates correspond to the initial peak value for each of the two parameters for combinations which were initiated by /k/, regardless of the following consonant(s), and even if the first peak was actually reached during a following [s] segment. Nevertheless, it is clearly shown here that, in addition to the highly positive correlation as a whole, the peak values of both parameters seem to be categorized according to the manner of the initial voiceless obstruents : The first local maximum opening as well as the peak abductor activity are generally larger for the sequences proceeding from [s] than those from [k]. It should be mentioned here that most of the "K" points, except for the three which correspond to the single word-initial, word-final, and geminated /k/, are always reached during the following [s] segments. In addition, previous reports on single voiceless obstruent production (e.g., Sawashima, 1970) revealed that there was a large opening of the glottis for voiceless fricative /s/, and a relatively small opening for voiceless stop /k/. Therefore it is conceivable that these peak values are more closely linked, not to the segments during which the peaks are reached, but to the initial segments from which those peaks start being reached, as far as the first opening phase during sequential voiceless obstruent production is concerned. Incidentally, the two points "S" embedded in the "K" group correspond to the word-final /s/ in /s # v/ and /s # k/, while the lowest valued "K" is the word-final /k/ in /k # v/. It should be emphasized that, in these exceptional cases, the first peak openings correspond to a single voiceless obstruent /s/ or /k/ which is immediately followed by a word boundary.

Figure 12 presents the timing of the first local maximum of the glottal opening during voiceless sequence production, using the averaged glottograms of 12 tokens each. In addition, two representative time courses of the original averaged glottograms are shown by the dashed lines only during their initial opening movements up through the first peak. The characters "S" and "K" are labeled according to the same method used for Fig. 11. From this figure, we conclude that the difference in the first local maximum value of the glottal opening found in the previous figure is related to a difference in the velocity of the glottal movement: The clusters beginning with an [s] segment are accompanied by a rapid initial opening, consequently attaining an early and larger local maximum value of glottal aperture. On the other hand, in the clusters beginning with a [k], the movement is gradual up to the first peak, even though the peak itself is reached during the following [s] segment if any exist. It thus appears that a fast separation of the vocal folds is preferable for the turbulent noise source during fricative segments; for stop production, however, such a rapid increase in glottal area seem unnecessary during initial stop closure to terminate vocal fold vibrations, to allow buildup of oral air pressure, and to prepare for following aspiration or frication noise, if required.

The current data are also important in explaining the phonetic realization of a word boundary. Let us assume for the moment that the word boundary in American English is manifested at the laryngeal level by a closing movement at the preceding word ending, followed by an opening movement at the following word initiation. A similar hypothesis was once proposed by

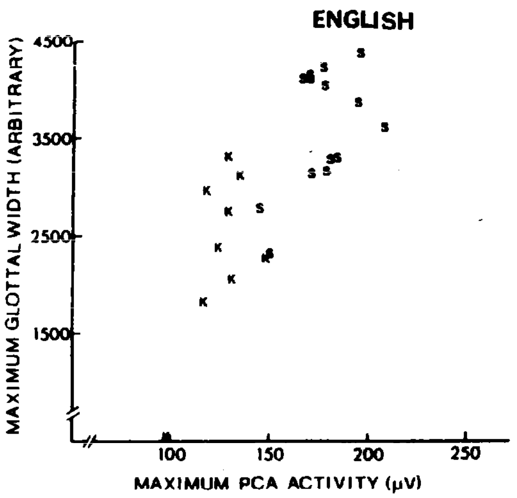

FIG. 11. The relationship between the first local maximum PCA activity and the first local maximum glottal opening during voiceless sequence production. "S" and "K" stand for the voiceless sequences beginning with /s/and /k/, respectively.

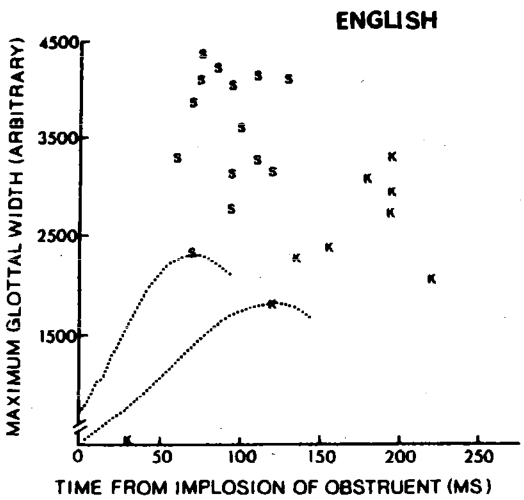

FIG. 12. The timing of the first local maximum glottal opening during voiceless sequence production. In addition, two representative time courses of the opening phase are included. Zero of time axis corresponds to the implosion of the first obstruent, which served as line-up point for the averaging. "S" and "K" stand for voiceless sequence beginning with /s/ and /k/, respectively.

p1622.djvu

Fujimura (1972), although it referred solely to Korean stop production. Our speculation could explain, for example, why the glottis temporarily narrows in the vicinity of the juncture during /s # k/ production and reopens for the following word-initial aspirated stop production. Moreover, not only the glottalization of the word-final /k/ and the glottal attack of the word-initial vowel production might be accounted for along these lines, but also the difference in the peak glottal opening between the word-final /s/ and the word-initial /s/ production. Of course, such an interpretation has several apparent defects; for instance, it does not explain the findings for the geminate cases, which were produced with a single opening gesture despite the word boundary. In addition, the peak value differences between the two opening gestures in the glottograms (shown in Fig. 9) and electromyograms (shown in Fig. 10) for /sk # sk/ production are rather contradictory, in that the peak values for the preceding word-final /sk # / are usually larger than those for the following word-initial / # sk/.

Another interpretation, which is biomechanical in nature, is that there is an upper and lower limit on the velocity of glottal opening and closing gestures during speech. Here, the lower limit implies that a static open position of the glottis is unlikely to occur or at least difficult to maintain in running speech; and the glottal area is therefore continuously changing. The upper limit simply means that the velocity of glottal abduction and adduction cannot exceed a certain value. Under this hypothesis, the general tendency towards multiple glottal opening and closing gestures during most of longer voiceless clusters is due to the lower limit: Glottal articulation is "cyclical" in nature, rather than to keep a certain constant opening. On the other hand, the mono-modal pattern observed in voiceless geminate production is explained by the upper limit: If a geminate required two opening gestures and a temporary narrowing were necessary, the glottis would have to open, close, and reopen very quickly. On condition that this assumption is eventually demonstrated as correct across subjects, speaking rate should substantially affect the number of peaks found in the glottal opening curve during sequential production of unvoiced sounds, as was suggested by Frøkjaer-Jensen *et al.* (1971).

ACKNOWLEDGMENTS

This work was supported by NINCDS Grants NS-13617 and NS-13870, and BRS Grant RR-05596 to Haskins Laboratories. We are grateful to Thomas Baer for participating as the subject, to David Zeichner and Richard Sharkany for technical assistance, and to Agnes McKeon for preparing the illustrations.

[1]We have recently discussed the advantage of simultaneous recordings of photo-electric glottograms and fiberoptic films. (Löfqvist and Yoshioka, 1980).

[2]The deceptive shortness of the stop closure period, for example, in the audio envelope corresponding to each EMG curve should be attributed to the averaging method, while the continuous noise in the audio signals for the movement data is mainly due to the motor of the cine camera.

Basmajian, J., and Stecko, G. (1962). "A new bipolar indwelling electrode for electromyography," J. Appl. Physiol. 17, 849.

Dixit, R. P. (1975). "Neuromuscular aspects of laryngeal control: with special reference to Hindi, unpublished doctoral dissertation," University of Texas, Austin.

Fant, G., and Scully, C., Eds. (1977). "The larynx and language," Phonetica 34, 245–324.

Frøkjaer-Jensen, B., Ludvigsen, C., and Rischel, J. (1971). "A glottographic study of some Danish consonants," in *Form and Substance*, edited by L. L. Hammerich, R. Jakobson, and E. Zwirner (Akademisk Forlag, Copenhagen), pp. 123–140.

Fujimura, O. (1972). "Acoustics of speech," in *Speech and Cortical Function*, edited by J. H. Gilbert (Academic, New York), pp. 107–165.

Fujimura, O., and Sawashima, M. (1971). "Consonant sequences and laryngeal control," Research Institute of Logopedics and Phoniatrics, University of Tokyo, Annu. Bull. 5, 1–6.

Hirano, M., and Ohala, J. (1969). "Use of hooked-wire electrodes for electromyography of the intrinsic laryngeal muscles," J. Speech Hear. Res. 12, 362–373.

Hirose, H. (1976). "Posterior cricoarytenoid as a speech muscle," Ann. Otol., Rhinol. Laryngol. 85, 334–343.

Hirose, H., and Gay, T. (1972). "The activity of the intrinsic laryngeal muscles in voicing control: An electromyographic study," Phonetica 25, 140–164.

Hirose, H., and Gay, T. (1973). "Laryngeal control in vocal attack: An electromyographic study," Folia Phoniatrica 25, 203–213.

Hirose, H., Gay, T., and Strome, M. (1971). "Electrode insertion technique for laryngeal electromyography," J. Acoust. Soc. Am. 50, 1449–1450.

Iwata, R., and Hirose, H. (1976). "Fiberoptic acoustic studies of Mandarin stops and affricates," Research Institute of Logopedics and Phoniatrics, University of Tokyo, Annu. Bull. 10, 47–60.

Jakobson, R., Fant, G., and Halle, M. (1951). *Preliminaries to Speech Analysis: The Distinctive Features and their Correlates* (MIT, Cambridge, MA).

Kagaya, R. (1974). "A fiberoptic and acoustic study of the Korean stops, affricates and fricatives," J. Phon. 2, 161–180.

Kagaya, R., and Hirose, H. (1975). "Fiberoptic electromyographic and acoustic analysis of Hindi stop consonants," Research Institute of Logopedics and Phoniatrics, University of Tokyo, Annu. Bull. 9, 27–46.

Kewley-Port, D. (1977). "EMG signal processing for speech research," Haskins Laboratories Status Report on Speech Research SR-50, 123–146.

Lindqvist, J. (1972). "Laryngeal articulation studied on Swedish subjects," Quarterly Progress and Status Report, Speech Transmission Laboratory, Royal Institute of Technology, Stockholm 2/3, 10–27.

Lisker, L., Abramson, A., Cooper, F. S., and Schvey, M. H. (1969). "Transillumination of the larynx in running speech," J. Acoust. Soc. Am. 45, 1544–1546.

Löfqvist, A. (1976). "Closure duration and aspiration for Swedish stops," Working Papers, Phonetic Laboratory, Department of General Linguistics, Lund University 13, 1–39.

Löfqvist, A. (1978). "Laryngeal articulation and junctures in the production of Swedish obstruent sequences," in *Nordic Prosody (Travaux de l'Institut de Linguistique de Lund XIII)*, edited by E. Gårding, R. Bruce, and R. Bannert (Lund U. P., Lund), pp. 73–83.

Löfqvist, A., and Yoshioka, H. (1980). "Laryngeal activity in Swedish obstruent clusters," J. Acoust. Soc. Am. 63, 792–801.

p1623.djvu

Pétursson, M. (1976). "Aspiration et activité glottale," Phonetica 33, 169–198.

Pétursson, M. (1978). "Jointure au niveau glottal," Phonetica 35, 65–85.

Sawashima, M. (1970). "Glottal adjustments for English obstruents," Haskins Laboratories Status Report on Speech Research SR–21/22, 187–200.

Sawashima, M. (1971). "Devoicing of vowels," Research Institute of Logopedics and Phoniatrics, University of Tokyo, Annu. Bull. 5, 7–13.

Sawashima, M. (1976). "Current instrumentation and techniques for observing speech organs," Technocrat 9–4, 19–26.

Sawashima, M., and Hirose, H. (1968). "A new laryngoscopic technique by use of fiberoptics," J. Acoust. Soc. Am. 43, 168–169.

Sawashima, M., and Niimi, S. (1974). "Laryngeal conditions in articulations of Japanese voiceless consonants," Research Institute of Logopedics and Phoniatrics, University of Tokyo, Annu. Bull. 8, 13–17.

Stevens, K. (1971). "Airflow and turbulent noise for fricative and stop consonants: Static considerations," J. Acoust. Soc. Am. 50, 1180–1192.

Yoshioka, H. (1979). "Laryngeal adjustments during Japanese fricative and devoiced vowel production," Haskins Laboratories Status Report on Speech Research SR–58, 147–160.