Laryngeal activity in Swedish obstruent clusters[a]

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Laryngeal articulatory movements and their coordination with supralaryngeal events have proved to be important for control of voicing and pre- and post-aspiration in obstruents. A reciprocal pattern of activity generally has been observed among laryngeal abductor and adductor muscles in the control of glottal opening in voiceless obstruent production. Current notions about laryngeal articulatory control rest, however, mainly on studies using simple linguistic materials, where voiced and unvoiced segments alternate in a regular manner. The present study examines laryngeal activity in voiceless obstruent clusters using the combined techniques of electromyography, fiberoptic filming, and transillumination of the larynx. The results indicate that laryngeal articulatory movements are precisely coordinated with the oral articulations of clusters to meet the aerodynamic requirements of speech production. Several laryngeal movements may occur in a cluster. Comparison of temporal patterns of glottal area variations obtained by fiberoptic filming and by transillumination of the larynx, showed them to be practically identical.

PACS numbers: 43.70.Bk

INTRODUCTION

Technical developments in recent years have provided means for a better understanding of laryngeal activity in speech. Application of electromyographic, fiberoptic, and glottographic techniques has advanced our knowledge of the control of laryngeal articulatory movements and their coordination with supralaryngeal events in speech production. In particular, the important role of the larynx and of laryngeal-oral coordination for producing contrasts of voicing and of pre- and post-aspiration in obstruents have been clarified for several different languages (Löfqvist, in press).

Glottal opening during voiceless obstruent production has been shown to be controlled by the posterior cricoarytenoid (abduction) and the interarytenoid (adduction) muscles (Hirose, 1976; Hirose, Yoshioka, and Niimi, 1978). For these two muscles, a reciprocal pattern of activation generally has been observed, whereas the role of other adductor muscles, such as the lateral cricoarytenoid, is more uncertain. The lateral cricoarytenoid is usually suppressed for both voiced and voiceless obstruents, and has been functionally grouped with the vocalis muscle (Hirose and Gay, 1972; Hirose and Ushijima, 1978). It should be noted, however, that the notion of strict reciprocity between the posterior cricoarytenoid and the interarytenoid muscles rests mainly on studies using combinations of consonants and vowels, where voiced and unvoiced segments alternate in a regular manner.

Laryngeal activity in clusters of voiceless obstruents has not been dealt with in any comparable detail. Fujimura and Sawashima (1971) investigated a limited number of voiced and voiceless stop combinations in American English using fiberoptic filming. Löfqvist (1977, 1978) studied Swedish voiceless obstruent clusters using transillumination of the larynx and aerodynamic records. Pétursson (1978) applied the same techniques to Icelandic obstruent combinations.

The results of the Swedish and Icelandic studies indicated that a sequence of two voiceless obstruents could be produced with one or two separate glottal opening and closing gestures. Combinations of voiceless stop + voiceless fricative, or voiceless fricative + voiceless unaspirated stop generally contained only one glottal articulatory gesture, with peak glottal opening occurring during the fricative. Similarly, two consecutive voiceless stop consonants were produced with one laryngeal gesture, the timing of which varied with the presence or absence of aspiration after the release of the second stop. On the other hand, a sequence of voiceless fricative + voiceless aspirated stop usually contained two separate laryngeal gestures with peak glottal opening during the fricative and just before stop release; between the two maxima of glottal opening the vocal folds were adducted without complete glottal closure.

Due to the limited number, and scope, of investigations using more complex linguistic material, it seems important to determine whether established notions about laryngeal function also are valid for laryngeal control in clusters of voiceless obstruents, where the control of the larynx, in terms of laryngeal "coarticulation," may differ from that in single obstruents. In doing so it is, moreover, important to obtain simultaneous information on both glottal articulatory movements and the activity of the muscles assumed to be responsible for these movements. In the absence of such information, it may be difficult to determine either the specific effects of different muscular activity patterns, or whether observed movements are actually caused by muscular and/or nonmuscular, e.g., aerodynamic, forces.

The transillumination technique, or photoglottography (Sonesson, 1960), has been in regular use for several years, but it has not been extensively compared with other techniques for obtaining information on laryngeal behavior in speech. Such comparisons have mostly involved transillumination and electrical glottography during steady vowel phonation (e.g., Frøkjaer–Jensen, 1968: Köster and Smith, 1970; Kitzing, 1977; Kitzing and Löfqvist, 1978). Two studies of phonation, comparing variations in glottal area measured from high-speed films and transillumination signals (Coleman and Wendahl, 1968; Harden, 1975), reported conflicting evidence concerning the reliability of the transillumination technique. No study has compared information on dynamic patterns of laryngeal articulations obtained by transillumination and by other methods. Since this is an area where the transillumination technique may be most useful, it appears important to evaluate its possibilities and limitations for this kind of research.

The aim of the present study is twofold: To contribute to a better understanding of laryngeal control in consonant production, and to assess further the transillumination technique as a tool for studying laryngeal behavior in speech.

I. METHOD

A. Procedure

Electromyographic recordings were obtained from the posterior cricoarytenoid (PCA) and the interarytenoid (INT) muscles. Bipolar, hooked-wire electrodes (Basmajian and Stecko, 1962; Hirano and Ohala, 1969), consisting of a pair of platinum–tungsten alloy wires (50μ in diameter with isonel coating), were inserted perorally under indirect laryngoscopy with the aid of a specially designed, curved probe. Before the insertion, surface anesthesia (4% Xylocaine) was applied to the pharyngeal and laryngeal mucosa. The insertion technique, and the placement of the electrodes have been described by Hirose (1971). For verification of electrode position, the subject performed selected nonspeech and speech maneuvers, such as breathing, swallowing, pitch changes, voiced and voiceless sounds; during these maneuvers the EMG signals were monitored on an oscilloscope and over a loudspeaker. The EMG signals were recorded and processed with the Haskins Laboratory system (Kewley–Port, 1977). After amplification and high-pass filtering at 80 Hz, to remove movement artifacts and hum, the signals were recorded on a multichannel instrumentation tape recorder. For processing, the signals were full-wave rectified and integrated over a 5-ms window through linear-reset integrators, and fed into a computer at a sampling rate of 200 Hz. In the averaging process, the signals were aligned with reference to a predetermined, acoustically defined lineup point, and also further integrated over 35 ms.

The larynx was filmed through a flexible fiberscope (Olympus VF type O) at a film speed of 60 frames/s. The fiberscope, inserted through the nose, was kept in position by a specially designed headband. A syn-

chronization signal was recorded on one channel of the tape recorder for frame identification. Relevant portions of the film were analyzed frame by frame with a computer assisted analyzing system, and the distance between the vocal processes was measured as an index of glottal opening.

The light from the fiberscope was used as part of a transillumination system, whereby the amount of light passing through the glottis was sensed by a photo-transistor (Philips, BPX 81), placed on the surface of the neck just below the cricoid cartilage, and held in position by a neckband. The signal from the transistor was amplified and recorded on one channel of the tape recorder. For averaging, the transillumination signal was sampled at 200 Hz and fed into the computer. It was aligned with the EMG signals and integrated over 5 ms.

The measurements from the film were combined with the transillumination signals obtained for the same tokens of the test utterances. No further processing was applied to the measurements from the film.

A direction-sensitive microphone was used to record the audio signal in direct mode on one channel of the instrumentation recorder and also on an ordinary tape recorder at a recording speed of 7.5 ips. The audio signal was used for determination of the lineup points and also included in the further processing. It was sampled at 10 kHz using the Haskins PCM system and then rectified and analyzed in parallel with the electrical and biomechanical signals. In the averaging process, the rectified audio signal was integrated over 15 ms.

B. Linguistic material

The linguistic material consisted of Swedish voiceless obstruents and obstruent clusters in various positions, with a word boundary preceding, following, or intervening within, the cluster. Both the transillumination technique and fiberoptic filming require a wide pharyngeal cavity, which had to be taken into account in selecting the linguistic material. Swedish words were used, and these words are given in Table I. All the words in Set A were combined with those in Set B and placed in the carrier phrase "Men. . . " ("But . . . ") to yield 24 normal Swedish sentences.

Swedish voiceless stops are aspirated in prestress position and unaspirated when they immediately follow

TABLE I. The linguistic material. All the words in set A were combined with those in set B. The words in set A are proper names, those in set B present tense of verbs.

Set A		Set B	
Li	[li:]		
Lis	[li:s]	ilar	[i:lar]
Ek	[e:k]	silar	[si:lar]
Liszt	[list]	pilar	[pʰi:lar]
Eks	[e:ks]	spelar	[spe:lar]
Kvists	[kʰvists]		

a stressed vowel or /s/. Although this difference between aspirated and unaspirated voiceless stops is not phonemic in Swedish, when aspiration occurs it serves as one of the cues for the distinction between voiced and voiceless stops, since the former are always unaspirated. In addition, the presence or absence of aspiration in voiceless stops in some contexts marks the location of a word boundary. Word initial stressed vowels in Swedish are usually produced with a glottal attack at the onset.

A native male speaker, one of the authors, read the whole material 20 times from randomized lists. Ten to fifteen repetitions of each utterance type were used for averaging. Fiberoptic films were made during 2–5 of the repetitions.

II. RESULTS

A. Transillumination and fiberoptics

Patterns of glottal area variations measured from fiberoptic films and by transillumination are shown in Figs. 1 and 2. The movement patterns obtained by the two techniques were practically identical. This was also shown by a correlation analysis. For each of 56 utterances, a Pearson product moment correlation coefficient was calculated between the two curves. The correlation coefficients were highly significant (all r's > 0.90, with $P < 0.001$ in all cases).

In some instances articulatory movements of the root of the tongue and the epiglottis interfered with the passage of light from the fiberscope to the larynx, cf. "Ek spelar" in Fig. 2. These instances could be readily identified by a sudden decrease in the amplitude of the transillumination signal, which lacked any counterpart in the measurements from the film. Inspection of the corresponding film frames indicated that in these cases the view of the anterior portion of the glottis was blocked.

B. Laryngeal articulatory movements

Since the temporal patterns of glottal area variations obtained by transillumination and by fiberoptic filming showed a high correlation and were practically identical, only those obtained by transillumination will be discussed below. The variability among individual tokens of the same utterance type was rather small as shown in Fig. 3. The most obvious variation in Fig. 3 is that /s ≠ s/ in "Kvists silar" is produced with a single glottal opening gesture, with or without an extra adjustment for maintaining an open glottis throughout the period of frication. We shall therefore focus our attention mainly on the average curves.

In single voiceless obstruents, shown in Fig. 4, laryngeal articulatory movements usually have the form of a single "ballistic" opening and closing gesture. Some variation in this gesture can be found for fricatives and aspirated stops. In particular, peak glottal opening occurs closer to implosion for the fricative than for the stop. The fricative glottal abduction is also accompanied by a higher velocity and a somewhat larger peak glottal opening.

Similar patterns are also found in clusters of voiceless obstruents. In a word initial cluster /≠sp/, in Fig. 5, where the stop is unaspirated according to Swedish phonology, one glottal gesture is found. This gesture is similar to the one found for a single voiceless fricative in Fig. 4, with peak glottal opening occurring during the fricative. Thus, the glottis begins to close before stop implosion.

When a word boundary occurs between /s/ and /p/, Fig. 5, and the stop is aspirated, two consecutive
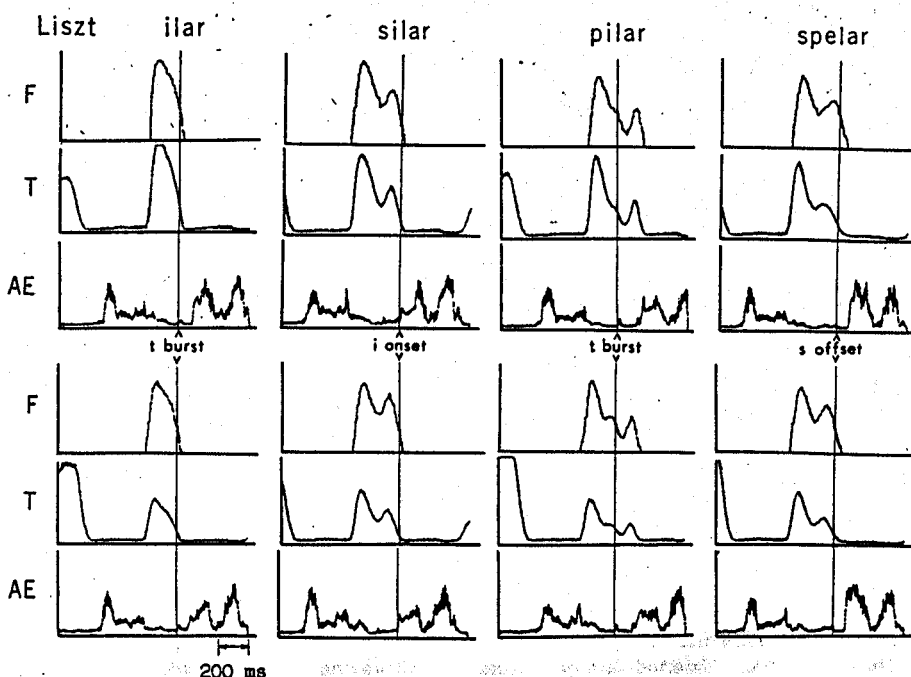

FIG. 1. Comparisons of fiberoptic and transillumination records for the utterances "Liszt ilar," "Liszt silar," "Liszt pilar," and "Liszt spelar." Two tokens of each utterance type are shown. F = glottal area obtained by fiberoptic filming. T = glottal area obtained by transillumination. AE = audio envelope.
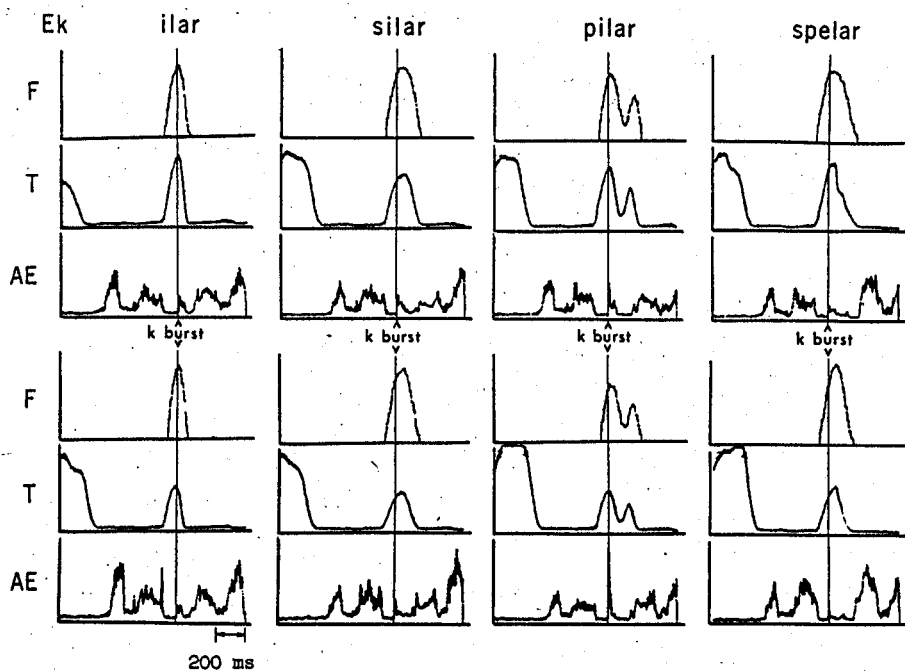
FIG. 2. Comparisons of fiberoptic and transillumination records for the utterances "Ek ilar," "Ek silar," "Ek pilar," and "Ek spelar." Two tokens of each utterance type are shown. Symbols as in Fig. 1.

gestures are found. Their shape and timing in relation to supraglottal events are similar to those found for the single obstruents above. Peak glottal opening occurs close to implosion for the fricative, and just before release of the stop. At the same time the vocal folds are adducted, though without complete glottal closure, between the two peaks of glottal opening. A minimum of glottal opening thus occurs just after stop implosion.
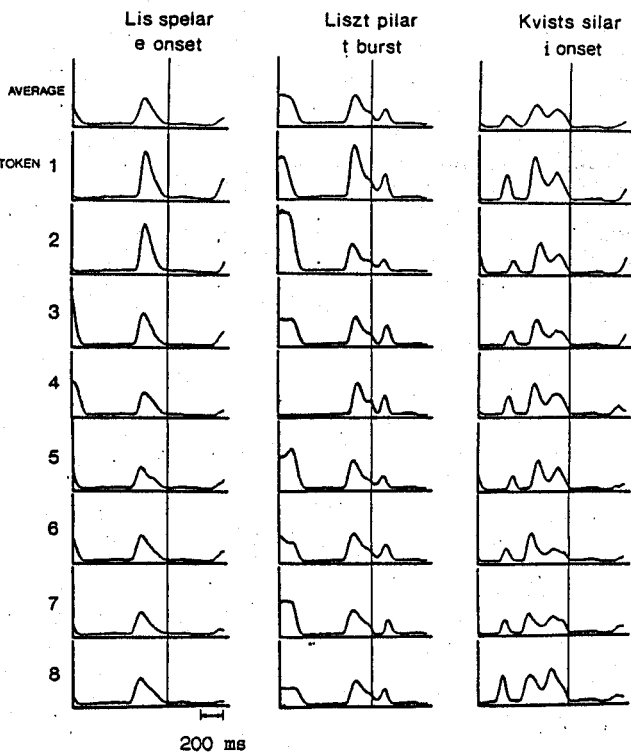

FIG. 3. Average and single token transillumination signals for the utterances "Lis spelar," "Liszt pilar," and "Kvists silar." Top row shows average curves, bottom eight rows show single tokens.

A similar cluster /st≠/ in word final position, Fig. 6 is produced with one laryngeal articulatory gesture, but its temporal course differs from that for /≠sp/ in Fig. 5. The glottis opens more quickly and closes more slowly so there is still some glottal opening at release of /t/. In accordance with the patterns discussed above, peak glottal opening occurs during the fricative.

In the cluster /st≠s/, Fig. 6, two separate gestures occur. The initial abduction is rapid, and the following adductory and abductory movements are slower. Peak glottal openings are found during the fricatives and a minimum of glottal opening just before stop release. For the cluster /st≠p/ in Fig. 6, the initial abduction gesture for the fricative and the gesture for the aspirated voiceless stop are similar to the ones already discussed. For the word final /t/, however, the pattern differs from that found in /st≠/ in the same figure, in that there is a small extra adjustment in contrast to the overall reduction in speed of glottal adduction noted before. Thus, the glottal gesture for the word final /t/ differs according to whether a glottal stop or a voiceless aspirated stop follows the word boundary.

In the cases discussed so far, a word boundary intervened within the cluster in those instances where several consecutive articulatory gestures occurred. Even in the absence of a word boundary, multiple laryngeal articulatory movements may occur. Fig. 7 presents the cluster /sts≠/ with two articulatory gestures. Their relationship to oral articulations is the same as the ones noted above. The same basic pattern is found in the cluster /sts≠p/ in the same figure with three separate gestures.

Two stops follow each other with an intervening word boundary in Fig. 8. Each stop is aspirated and produced with a separate laryngeal gesture. The timing of the gesture is similar for both of them, and almost identical with the gesture for a single stop in Fig. 4,
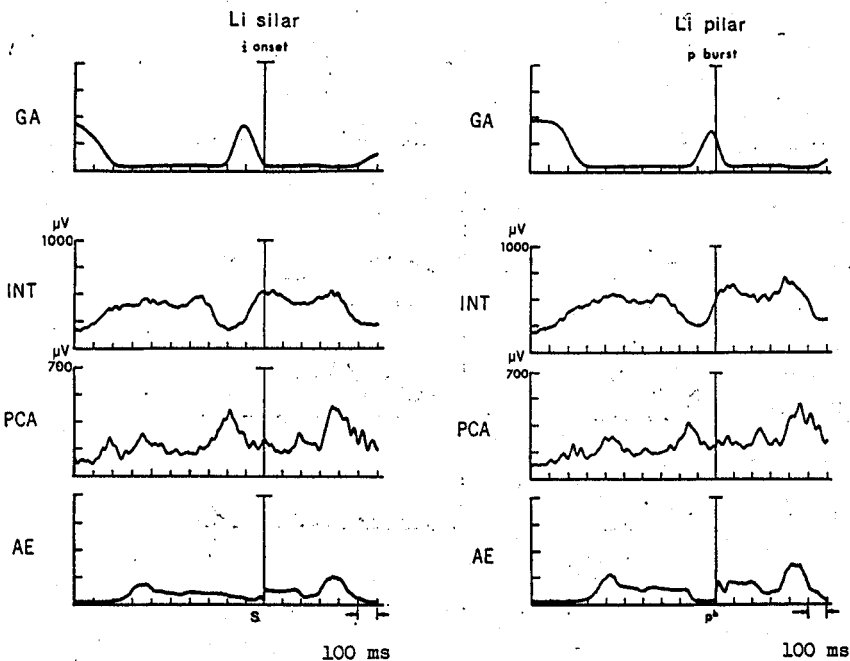
FIG. 4. Average transillumination signal (GA), INT and PCA EMG records, and audio envelope (AE) for the utterances "Li silar," and "Li pilar."

with peak glottal opening occurring just before release.

Figure 8 also presents the cluster /ks≠sp/. Here only one laryngeal gesture occurs with peak opening during the fricative. The abduction is rather slow and related to the occurrence of maximum opening. Glottal adduction is slow, and starts before implosion of the labial stop following the fricative.

C. Motor control of laryngeal articulatory movements

An inspection of the combined records of glottal movements and muscular activity patterns reveals that the articulatory movements are associated with distinct activity patterns in the posterior cricoarytenoid (PCA) and the interarytenoid (INT) muscles. This holds true irrespective of the number of glottal opening and closing gestures in the clusters. The activity patterns of PCA and INT show, in general, that these two muscles are activated for glottal abduction and adduction, respectively. The present results indicate, however, that during a voiceless obstruent cluster where the glottis is open, changes in glottal opening area seem mainly controlled by the PCA. When there are more than one opening and closing gesture during the cluster, as in Figs. 5, 6, 7, and 8, and the vocal folds are adducted without complete glottal closure, both the abduction and the adduction appear due to activation and inactivation of PCA, respectively. In these cases there may or may not be concomitant increased INT activity associated with the decrease in glottal opening area. Examples of increased INT activity can be seen in Fig. 5 ("Lis pilar"), Fig. 6 ("Liszt silar"), Fig. 7 ("Kvists pilar"), and Fig. 8 ("Ek pilar"). Examples of suppressed INT acitivity throughout the cluster occur in
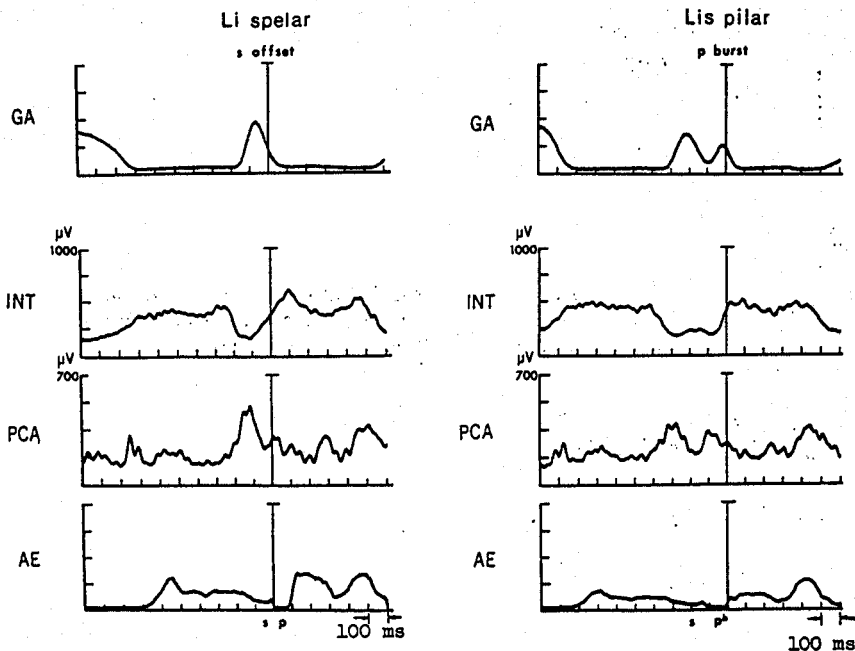

FIG. 5. Glottal area, EMG, and audio signals for the utterances "Li spelar," and "Lis pilar."
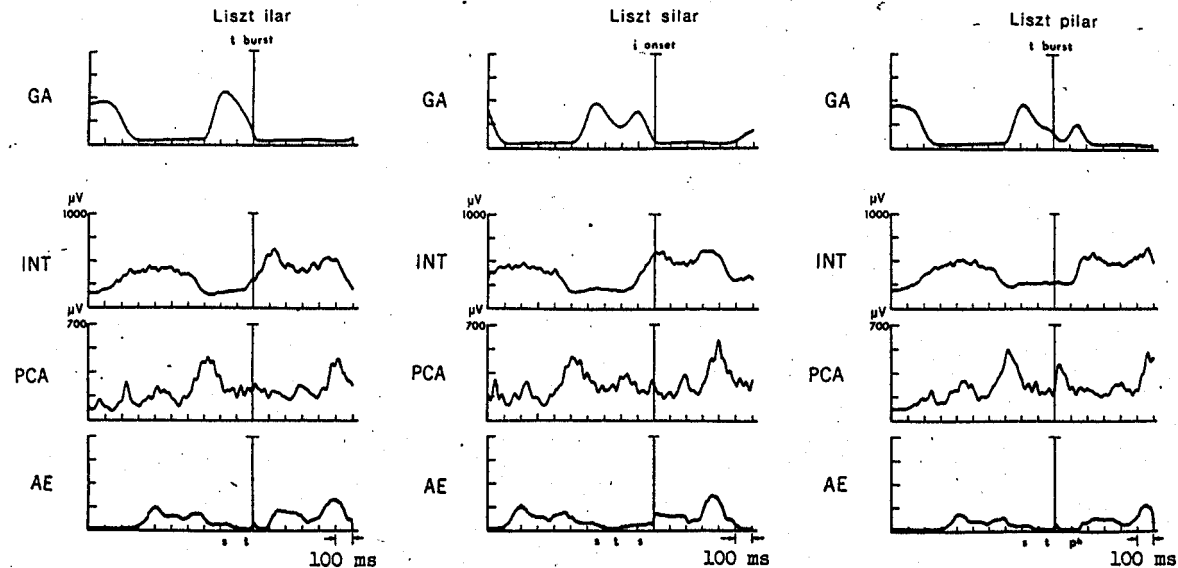
FIG. 6. Glottal area, EMG, and audio signals for the utterances "Liszt ilar," "Liszt silar," and "Liszt pilar."

Fig. 6 ("Liszt pilar") and Fig. 7 ("Kvists ilar"). In all clusters, the changes in PCA activity associated with the glottal movements during the cluster are much more salient than the changes in INT. Another observation is also relevant here. For "Liszt ilar" in Fig. 6 and, notably, "Eks spelar" in Fig. 8, the beginning of glottal adduction, i.e., peak glottal opening, occurs well ahead of the increase in INT activity, whereas the decrease in PCA activity occurs at the appropriate time. In these cases a decrease in PCA activity thus seems more directly related to initiation of glottal adduction than INT activity per se.

The differences between the voiceless fricative and the voiceless stop in Fig. 4 are only partially visible in the electromyographic records. Peak PCA activity is higher for the fricative than for the stop, and the decrease in INT activity is deeper and more rapid for the fricative. Comparisons between the cluster /≠sp/ in Fig. 5 and the cluster /st≠/ in Fig. 6 reveal that the longer glottal opening and the slower adduction in the latter are accompanied by a broader peak of PCA activity.

An illustration of the relationship between averaged PCA activity and glottal opening is presented in Fig. 9. The graph shows the peak PCA activity plotted against the associated peak glottal opening. It also plots the minimum PCA activity against the concomitant minimum glottal opening for those clusters where more than one glottal opening and closing gesture occurred. Although an overall positive relation is found between average PCA activity and glottal opening, it is evident in Fig. 9 that the same value of PCA activity can be associated with different degrees of glottal opening, and, conversely, that the same degree of glottal opening can
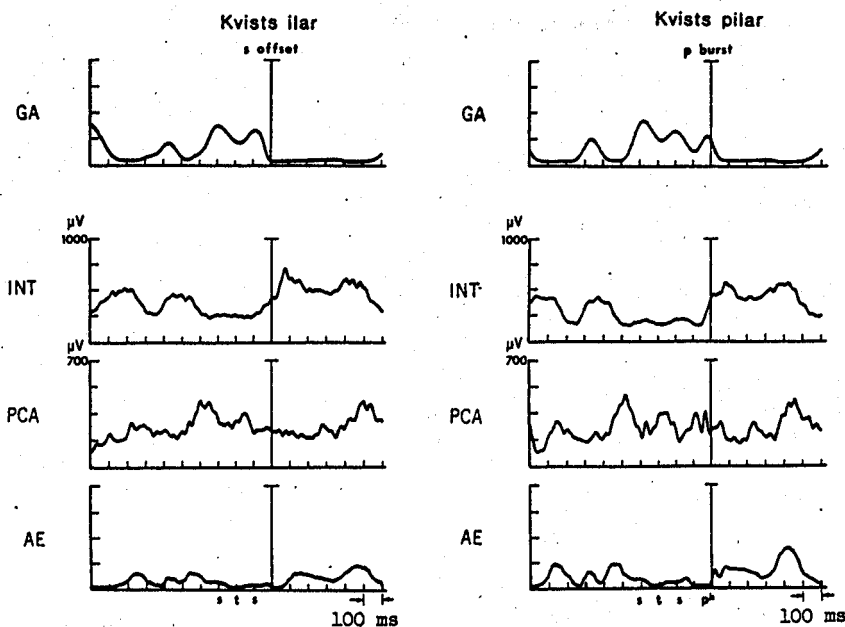

FIG. 7. Glottal area, EMG, and audio signals for the utterances "Kvists ilar," and "Kvists pilar."
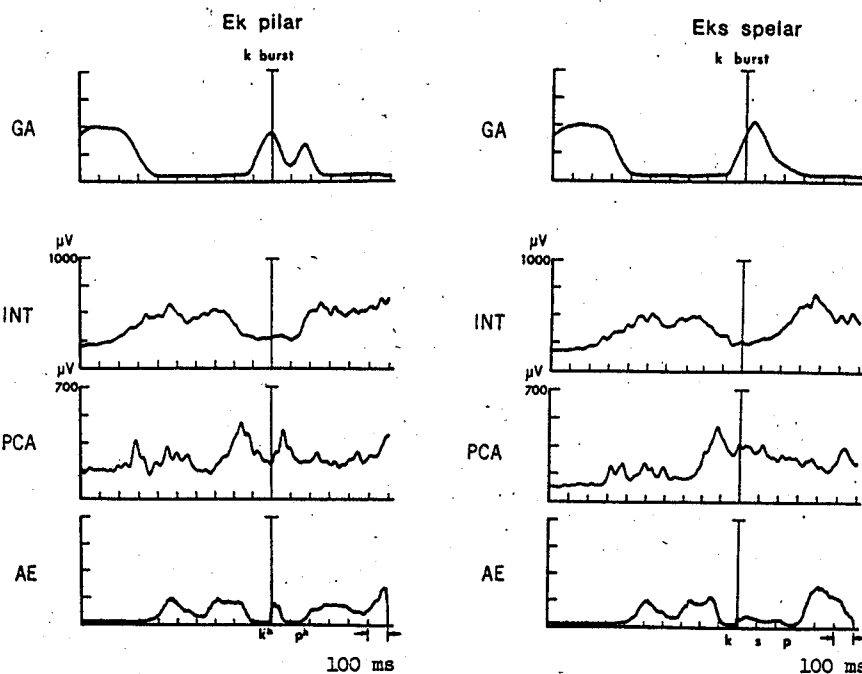
FIG. 8. Glottal area, EMG, and audio signals for the utterances "Ek pilar," and "Eks spelar."

occur with different levels of PCA activity. At the same time, some regularities do exist. When several glottal openings occur, the first one is generally larger and associated with higher PCA activity. Within one and the same utterance type, the temporal changes of glottal opening area and PCA activity level are monotonically related. This is indicated by the lines in the graph connecting different data points. These lines connect successive glottal states, and the associated

PCA activity level, within one and the same utterance type. For clarity of exposition only three sets of data points have been connected in this way, but a similar relationship holds true for the other utterance types as well.

III. DISCUSSION

The results of the present study show a high correlation between measures of glottal area variations obtained by fiberoptic filming and by transillumination. For this to hold true, it was necessary to position the phototransistor just below the cricoid cartilage. Placement of the transistor on the cricothyroid membrane made the system sensitive to vertical movements of the larynx. These movements resulted in baseline shifts related to the intonation pattern of the utterance, as well as in spuriously large glottal openings for velar sounds.

It is, at present, not possible to calibrate the transillumination system. Similarly, measurements made from fiberoptic films may contain some errors due to vertical movements of the larynx changing the distance between the glottis and the lens of the fiberscope. A better understanding of the relationship between the transillumination signal and the associated glottal opening can, in principle, be obtained by using transillumination in combination with a stereo-fiberscope (Fujimura, Baer, and Niimi, 1979).

From the results of the present study and those presented by Yoshioka, Löfqvist, and Hirose (1979), we may conclude that transillumination of the larynx gives as accurate a record of temporal patterns of glottal movements as fiberoptic filming. Correct placement of the phototransistor is necessary, however. At the same time the transillumination technique avoids the frame-by-frame analysis and the low sampling rate of filming. The output signal is convenient for further processing, and large amounts of data can be collected and pro-
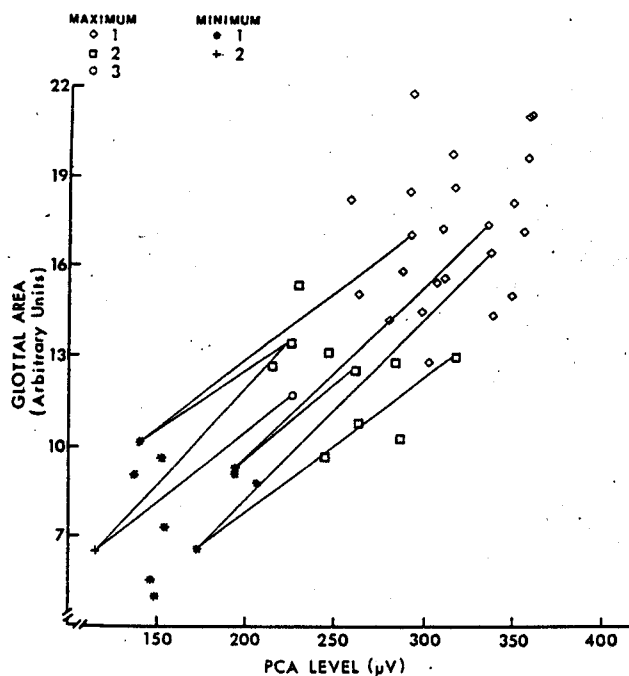

FIG. 9. Average glottal opening area plotted versus corresponding average PCA activity level. Maximum 1, 2, and 3 refer to first, second and third occurrence of peak glottal opening; minimum 1 and 2 refer to intervening minima of glottal opening. Lines connect successive glottal states for three utterances.

cessed in a short time. If a fiberscope is used as a light source, simultaneous films can be made at regular intervals during the recording session as a further control.

The present study is limited to a single subject. The overall patterns of glottal articulations in cluster production are, however, in general agreement with those obtained in studies using similar linguistic material in English (Yoshioka, Löfqvist, and Hirose, 1979) and Icelandic (Löfqvist and Yoshioka, in press). We thus have evidence from different speakers, and languages, that laryngeal activity in voiceless obstruent clusters is organized in one or more glottal gestures, and, furthermore, that these gestures are actively controlled by muscular adjustments.

In the present material, the initiation of glottal adduction in voiceless aspirated stops occurred before stop release. In this case, no aerodynamic factors could be responsible for the initiation of the gesture. In voiceless fricatives, the closing gesture started during a period of egressive air flow, and a Bernoulli effect could in theory assist in the adduction—in particular in the absence of PCA and INT activity. This does not seem likely, however, since calculations presented by Ishizaka and Matsudaira (1972) show that a negative pressure inside the glottis only occurs for small glottal openings, and the pressure is rather small. The glottal opening during voiceless fricatives is considerably larger than that during the open part of the glottal cycle in normal phonation.

It has been suggested that PCA and INT function in a reciprocal fashion (e. g., Hirose, 1976; Hirose and Ushijima, 1978). Although this is undoubtedly true in single voiceless obstruents, the material presented here suggests a slightly different picture. During a voiceless cluster, where the glottis stays open for a long period, variations in glottal area do occur. These variations can be controlled mainly by the PCA, whereas INT is suppressed during the whole cluster. At the same time, INT is clearly activated for a following vowel.

This conclusion is based on recordings from a single subject. Additional evidence supporting this conclusion can be found in the recordings published by Sawashima, Hirose and Yoshioka (1978). At the same time, their material also suggests that speakers may differ in their respective use of PCA and INT in controlling glottal opening in speech. The nature and extent of such individual differences are unknown at present due to the limited number of subjects investigated.

The notion of reciprocity would seem to imply that the activity levels of PCA and INT are inversely related to each other. The present material points to another possibility, i. e., both muscles may be more or less suppressed.

The qualitative nature of this interpretation should be emphasized, however. In the recordings discussed above, instances of incomplete glottal adduction were accompanied by suppressed PCA activity with none, or very little, INT activity. It is, however, impossible to infer the influence on vocal fold position of a parti-

cular muscle on the basis of electromyographic recordings alone. Due to varying tension-length relationships in muscles, as well as the influence of other muscles, tissues and mechanical arrangements of laryngeal joints, too many variables are unkown here to permit a detailed modeling. Even though the change in PCA activity during the clusters is much greater than that of INT, we cannot uniquely determine their respective contributions to glottal area change. Two other caveats should also be mentioned. The suppression of INT during the clusters was comparable to that during inspiration, when INT can be assumed to be inactive. However, the noise level in the recording sets a lower limit to the amount of suppression that can be detected. Thus, we do not know if additional changes in INT activity occurred during its periods of suppression, since such changes would be masked by the background noise. Only recordings with a better signal to noise ratio can decide this question. The second caveat concerns the possible role of other adductor muscles in the absence of INT activity. Due to the technical problems of making simultaneous recordings of several channels of bioelectrical and biomechanical information, we did not attempt to record from other adductor muscles. There is nothing in the published literature to suggest that they should be generally active in the absence of INT activity. Since the function of the different adductor muscles is not very well known, we are currently making additional recordings to clarify their role in obstruent cluster production.

In Fig. 9, a positive relationship is found between average glottal opening area and PCA activity. A similar relationship has been presented by Hirose (1976), and by Hirose and Ushijima (1978), and it is perhaps not a surprising finding considering the anatomical arrangement of the PCA. In view of the rather crude measures used, in particular average peak, or minimum PCA activity, and in view of possible non-linearities in the transillumination signal, some variability in the relationship can be expected. In addition, variations in speed of glottal gestures and in duration of PCA activity can also account for some of the variability. Furthermore, a linear plot may not be the most appropriate, but the relationship between the rectified and integrated EMG signal and the force generated by the muscle is not clear, in particular for non-isometric contractions (Bouisset, 1973). In the case of the first peak of glottal opening, Maximum 1 in Fig. 9, the initial condition of the glottis is the same, i. e., the glottis is in a phonatory position. For the second peak opening, Maximum 2, the initial condition is not invariant, since the data points for the preceding glottal state, Minimum 1, have different values on the y coordinate. The three points for Maximum 2 in the utterances connected by lines in Fig. 9 differ little in glottal area but more in PCA activity. At the same time, the associated preceding points, Minimum 1, also differ in these three cases. Here, similar glottal openings seem to be achieved by different amounts of PCA activity due to varying initial conditions. As can be expected, PCA activity thus seems more directly related to changes in glottal area than to glottal area per se.

The observed variations in glottal area are obviously related to various segmental properties of an utterance. The most apparent relation is that sounds requiring a high rate of air flow are produced with a separate glottal opening gesture.

It is possible that the observed incomplete glottal adduction is made to prevent excessive air flow, and waste of air during an ongoing utterance. Although there is probably some substance to such an argument in general, it is troublesome that adduction often is found during a stop closure, when no egressive air flow can occur. .

The difference in laryngeal movements between stops and fricatives in Fig. 4 is most likely related to different aerodynamic requirements for stop and fricative production. A rapid increase in glottal area would allow for the high air flow necessary to generate the turbulent noise source during voiceless fricatives (Stevens, 1971). In stops, the timing of glottal opening during the closure is part of the mechanism controlling aspiration (Löfqvist, in press).

Rather than trying to give narrow linguistic accounts of the variations in glottal opening encountered during voiceless obstruent clusters, it seems more reasonable to assume that they reflect both the encoding of linguistic information and the organization of the motor system itself. There are two points to be made here. The first concerns the nature of laryngeal control in speech. The second is related to motor control of coordinated movements in general.

There is little, if any evidence that the glottis ever opens and maintains a static open position in speech. Thus, for single voiceless obstruents, the glottis executes a continuously changing, "ballistic" opening and closing gesture, and in clusters one or more gestures can occur. This mode of glottal control seems to be a basic feature of laryngeal control, and thus constitutes the speech motor system's contribution to observed glottal movements. These laryngeal movements are precisely coordinated with supralaryngeal events to meet the aerodynamic requirements for producing a signal with a specified acoustic structure. This would constitute a superimposed linguistic timing of glottal movements.

It is possible that an active glottal opening and closing gesture is an inherent feature of articulatory units requiring a high rate of air flow and/or buildup of oral air pressure. Such units could consist of a single voiceless stop or fricative but also of clusters of stops and fricatives. The variations in glottal area during a voiceless cluster observed in the present study could thus follow from the temporal spacing of successive realizations of the articulatory gestures of different units.

There is a tight temporal coordination of laryngeal and oral articulations in voiceless obstruent production. In addition to the results of the present study, material presented in Löfqvist (1978) indicates that the interval from implosion to the occurrence of peak glottal opening in voiceless fricatives may remain almost constant, irrespective of variations in overall fricative duration. Similarly, Yoshioka, Löfqvist, and Hirose (1980) show that peak velocity of the glottal abduction gesture in voiceless sequences may occur at a fixed distance from the implosion of the first obstruent, in spite of variations in duration, size and timing of the gesture. The nature of this coordination constitutes an important problem for any theory of speech motor control.

Theories of speech production based on feature-spreading (e.g., Daniloff and Hammarberg, 1973; Hammarberg, 1976; Bladon, 1979; see also Fowler, 1980) would seem unable to account for this laryngeal-oral coordination, at least in their present form. One reason for this is that their temporal resolution is limited to quanta of phone or syllable size, whereas laryngeal-oral coordination in obstruents requires a finer grain of analysis. A more interesting account is offered by the theory of motor control proposed by Bernstein (1967), and elaborated by Greene (1971, 1972; see also Boylls, 1975; Turvey, 1977; Kugler, Kelso, and Turvey, 1980; Kelso, Holt, Kugler, and Turvey, 1980; Fowler, Remez, Rubin, and Turvey, 1980). Designed to cope with the number of degrees of freedom to be directly controlled, this theory views motor coordination in terms of constraints among muscles or groups of muscles that have been set up for the execution of specified movements. Areas of motor control where this theory has proved to be productive include locomotion (Grillner, 1975), posture control (Nashner, 1977), and hand coordination (Kelso, Southard, and Goodman, 1979). It thus constitutes a useful theoretical framework for speech production studies.

ACKNOWLEDGMENTS

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