

# The cricothyroid muscle in voicing control

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Initiation and maintenance of vibrations of the vocal folds require suitable conditions of adduction, longitudinal tension, and transglottal airflow. Thus manipulation of adduction/abduction, stiffening/slackening, or degree of transglottal flow may, in principle, be used to determine the voicing status of a speech segment. This study explores the control of voicing and voicelessness in speech with particular reference to the role of changes in the longitudinal tension of the vocal folds, as indicated by cricothyroid (CT) muscle activity.

Electromyographic recordings were made from the CT muscle in two speakers of American English and one speaker of Dutch. The linguistic material consisted of reiterant speech made up of CV syllables where the consonants were voiced and voiceless stops, fricatives, and affricates. Comparison of CT activity associated with the voiced and voiceless consonants indicated a higher level for the voiceless consonants than for their voiced cognates.

Measurements of the fundamental frequency ( $F_0$ ) at the beginning of a vowel following the consonant show the common pattern of higher  $F_0$  after voiceless consonants. For one subject, there was no difference in cricothyroid activity for voiced and voiceless affricates; in this case, the consonant-induced variations in the  $F_0$  of the following vowel were also less robust.

Consideration of timing relationships between the EMG curves for voiced and voiceless consonants suggests that the differences most likely reflect control of vocal-fold tension for maintenance or suppression of phonatory vibrations. The same mechanism also seems to contribute to the well-known difference in  $F_0$  at the beginning of vowels following voiced and voiceless consonants.

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## INTRODUCTION

For sustained vibrations of the vocal folds to occur, some physiological and aerodynamic conditions must be met (cf. van den Berg, 1958; Stevens, 1977; Titze, 1980). In the larynx, the vocal folds must be adducted to a suitable degree and the longitudinal tension of the folds must be adjusted within an appropriate range. In addition, a transglottal airflow is required. This flow is induced by a transglottal pressure drop, and it, in turn, induces variations in pressure within the glottis, depending on the shape and configuration of the vocal folds. When conditions for phonation are met, these variations in pressure and the movement of the vocal folds that they cause interact with each other to produce sustained vibrations (cf. Titze, 1986).

Manipulation of the conditions that are necessary for vibrations to occur can, in principle, also be used to control the cessation of voicing during periods of voicelessness in speech. Thus adduction/abduction and stiffening/slackening of the vocal folds and facilitation/inhibition of transglottal flow are all potential mechanisms for determining the voicing status of a speech segment. The roles of adduction/abduction and facilitation/inhibition of airflow are relatively well understood. However, there is no general agreement whether control of longitudinal tension of the folds is actually used to control voicing status. The present work is aimed

at clarifying the role of this potential mechanism.

Vocal-fold abduction is the mechanism most often associated with voicelessness in speech. The glottal abduction gesture is phased with respect to oral articulations to produce contrasts of aspiration, and its amplitude and duration also vary with consonant type (e.g., Löfqvist, 1980; Löfqvist and McGarr, 1987; Löfqvist and Yoshioka, 1980, 1984). However, glottal abduction in itself may not always be sufficient for preventing laryngeal vibrations.

Glottal abduction during speech production is usually combined with a decrease of the airflow through the glottis due to a supraglottal constriction. For voiceless stop consonants, there is a buildup of oral air pressure behind the supraglottal occlusion, and the pressure drop across the glottis is thus decreased. The glottal vibrations cease as the transglottal flow decreases and the glottal opening increases (cf. Yoshioka, 1984; Hirose and Niimi, 1987). Venting the vocal tract during the period of stop closure, thus restoring the transglottal flow, may sometimes result in glottal vibrations (Vencov, 1968; Perkell, 1976). For voiceless fricatives, where the supraglottal constriction is incomplete, there is greater airflow than for stops, but the decrease in transglottal pressure drop in combination with the glottal abduction gesture may cause cessation of glottal vibrations. On the other hand, for the laryngeal fricative /h/, an abduction gesture is often found but the vibrations may still continue; in this case, no supraglottal constriction is made and the transglottal flow continues uninterrupted. Thus the laryngeal abduction gesture may not in itself arrest glottal vibrations but do so only in combination with aerodynamic factors (cf. Yoshioka, 1981). The interaction between glottal abduction

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and aerodynamic factors results in a subtle difference between the voicing offsets of voiceless stops and fricatives. Vibrations generally end at a larger glottal opening for fricatives than for stops (Hirose and Niimi, 1987). This fact could be related to the different aerodynamic conditions prevailing at the onset of stop closure and fricative constriction, respectively. In the former case, the vocal tract is completely sealed off, and the airflow through the glottis decreases abruptly. For fricatives, on the other hand, transglottal flow continues throughout the period of oral constriction even though the oral pressure is increased behind the constriction. Even during stop occlusion, aerodynamic factors may be used to facilitate or inhibit glottal airflow, thus contributing to the voicing distinction. This is accomplished through control of supraglottal volume. Active or passive expansion of the vocal tract facilitates voicing while tensing it or actively constricting it inhibits voicing (cf. Minifie *et al.*, 1974; Bell-Berti, 1975; Westbury, 1983).

Muscular control of the abduction gesture for devoicing involves suppression of activity in the interarytenoid, lateral cricoarytenoid, and thyroarytenoid muscles, and activation of the posterior cricoarytenoid. In comparison, for (unaspirated) voiced consonants, there may be some suppression of the adductors, but the posterior cricoarytenoid is not active.

While glottal abduction is the laryngeal gesture commonly associated with an arrest of glottal vibrations, its opposite, increased glottal adduction, can also be used for the same purpose. In this case, a tight closure is produced, preventing transglottal flow. Such an adjustment occurs for glottal stops and also for voiceless ejective and ingressive consonants (cf. Hirose and Gay, 1973; Fre Woldu, 1985). Electromyographic recordings of intrinsic laryngeal muscles suggest that the thyroarytenoid muscle is active in this case, adducting the folds and increasing the tension of their bodies.

While changes in glottal abduction/adduction and transglottal flow are certainly used for arresting glottal vibrations, it is more uncertain if the remaining possible mechanism—increased longitudinal tension—is used in speech for the same purpose. This mechanism was suggested by Halle and Stevens (1971) on theoretical grounds, but the evidence supporting it has been equivocal.

Physiological studies have shown that the cricothyroid muscle is most consistently associated with changes in the longitudinal tension of the vocal folds. This muscle controls the length and tension of the vocal folds by rotating the cricoid and thyroid cartilages relative to each other (e.g., Sonesson, 1982). Changes in vocal-fold tension result in changes of fundamental frequency during phonation, and thus cricothyroid muscle activity is highly correlated with fundamental frequency.

Another muscle that could also be involved in the control of the tension of the vocal folds is the vocalis muscle. EMG recordings from the vocalis indicate that it is active for both adduction of the vocal folds and changes in tension (cf. Löfqvist *et al.*, 1984); in particular, it adjusts the relative tensions of the vocal-fold body and cover. Although the experimental evidence is unclear, the vocalis most often shows reduced activity for voiceless consonants.

While the experimental results are conflicting, some EMG studies have suggested that the activity of the cricothyroid muscle is higher for voiceless than for voiced consonants. Dixit and MacNeilage (1980) reported that the cricothyroid was more active during voiceless than during voiced stops, fricatives, and affricates in Hindi. Löfqvist *et al.* (1984) showed that the cricothyroid was more active just before the beginning of the oral closure/constriction for voiceless as opposed to voiced consonants in Swedish. Other studies reviewed by Sawashima and Hirose (1983) also suggest a similar difference. However, Hirose and Ushijima (1978) suggested that these observed differences in CT level could have been associated with differences in the intonation patterns for the utterances involved. Several other investigators report no difference in the CT activity level associated with voiced–unvoiced pairs (e.g., Collier *et al.*, 1979; Kaga and Hirose, 1975). If such a relative increase in cricothyroid activity for voiceless consonants occurs, it could be related to the well-known higher fundamental frequency of a vowel following a voiceless consonant as compared to a vowel following a voiced consonant (e.g., House and Fairbanks, 1953; Lehiste and Peterson, 1961; Hombert *et al.*, 1979; Ohde, 1984). This phenomenon served as the impetus for hypothesizing a role for laryngeal tension in the voicing distinction. However, the lack of experimental evidence showing a systematic difference in CT activity has led investigators to seek alternate explanations for this phenomenon, such as articulatory and aerodynamic explanations.

There is thus conflicting evidence concerning the role of variations in the longitudinal tension of the vocal folds in the control of voicelessness. The present study was therefore designed to further investigate the activity of the cricothyroid muscle in voicing control using electromyographic techniques.

## 1. METHODS

Electromyographic recordings were obtained from the cricothyroid muscle in three subjects. Two of the subjects, one male (TB) and one female (NSM), were native speakers of American English; the third subject (LB), was a male native speaker of Dutch.

The linguistic material consisted of reiterant speech modeled after the sentence “The man went to market” (the underline indicates main lexical stress). Different CV syllables, drawn from 16 consonants and 3 vowels, were reiterated to form 48 different utterance types. The vowels used for the reiterant syllables were /i a u/ and the consonants were voiced and voiceless stops (/p b t d k g/), fricatives (/f v θ ð s z ʃ ʒ/), and affricates (/tʃ dʒ/). Only stops and fricatives were used for the Dutch subject. For the analysis of voicing contrasts, we used the consonant occurring in the syllable carrying the sentence stress in the utterance, i.e., the second syllable in the sentence. Five to ten repetitions of each utterance type were obtained.

Hooked-wire electrodes were inserted percutaneously under topical anesthesia of the skin. Verification of electrode position was made by having the subject perform selected speech and nonspeech gestures, such as pitch changes, vocal attacks, jaw movements, and swallowing. Placement into the

CT was verified by showing activity correlated with  $F_0$  but not with adduction, abduction, or jaw opening, and a characteristic pattern of activation and suppression during swallow. After amplification and high-pass filtering at 80 Hz, the signals were recorded on an FM tape recorder together with the speech signal. For averaging, the signals were full-wave rectified, integrated over a 5-ms window, then sampled and digitized, resulting in a computer 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 smoothed using a 35-ms triangular window. The lineup point for fricatives and affricates was the apparent end of frication. The lineup point for stops was the release burst. This point was chosen because it clearly marks the end of the period in which differing activity would be expected, if it were associated with the voicing distinction. Alternatively, we could have chosen the point of stop closure or onset of frication. However, in the present study, we have chosen to concentrate more on the CV rather than the VC junction.

In order to obtain a single numerical value for the level of cricothyroid activity, the area under the EMG curve for each token was calculated during a short time window. This window was chosen so as to cover the period of consonant occlusion and part of the preceding vowel; its end always coincided with the lineup point. The duration of the window

was chosen individually for each subject and consonant type based on acoustic measurements. Typical values were 125 ms for stops, 175 ms for fricatives, and 150 ms for affricates. The position of the window was based on theoretical and empirical considerations. If an increase in the tension of the vocal folds is used to suppress glottal vibrations, the neuromuscular events ought to occur within this window. They would be expected to begin near the transition from the voiced vowel to the voiceless consonant. This is also the point at which Löfqvist *et al.* (1984) found an increase in cricothyroid activity for voiceless consonants.

Measurements were also made of the fundamental frequency at the beginning of the vowel following the consonant. For this, the durations of the first ten pitch periods of each token were measured interactively on a computer. To keep the measurement task manageable, these measurements were only made for utterances containing the vowel /a/.

## II. RESULTS

### A. Electromyography

The averaged electromyographic curves for each of the three subjects are shown in Figs. 1–3; in these averages, the utterances containing different vowels have been pooled, since there were no systematic differences across vowels. For the present analysis and display purposes, data have also been pooled across place of articulation for the stops and

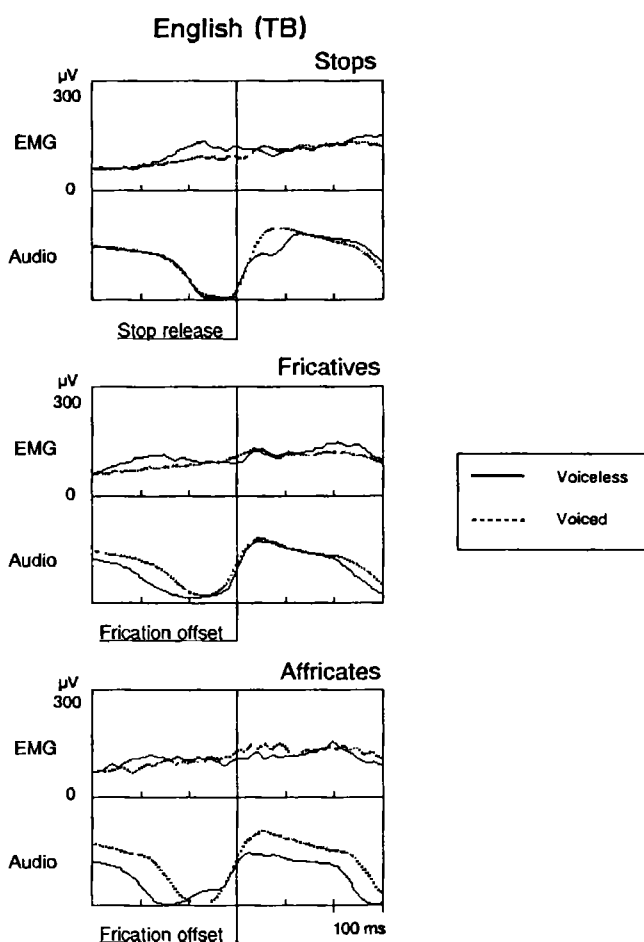


FIG. 1. Average EMG and audio signals for subject TB ( $n = 47$  for the stops and fricatives and 15 for the affricates).

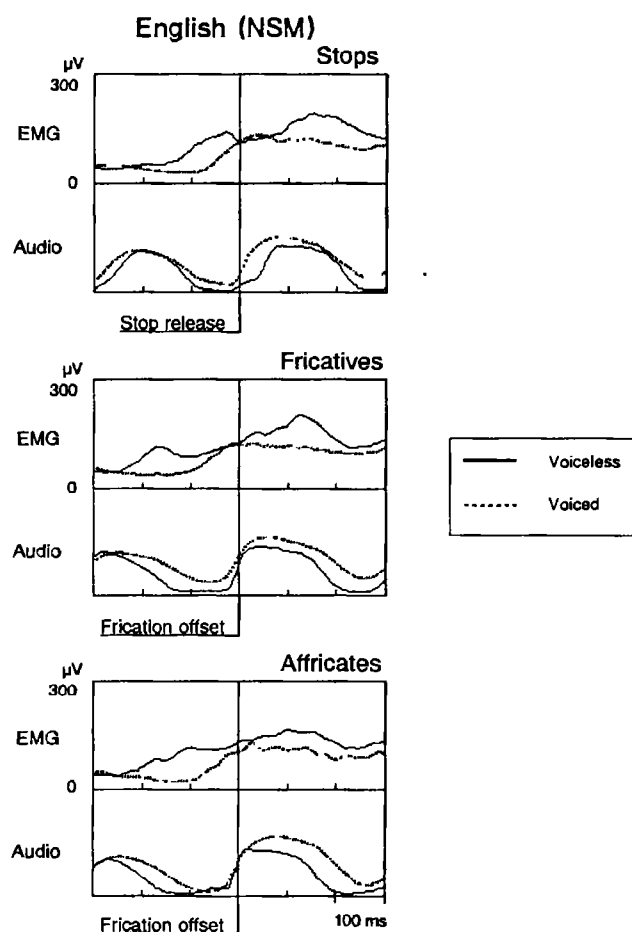


FIG. 2. Average EMG and audio signals for subject NSM ( $n = 89$  for the stops, 120 for the fricatives, and 28 for the affricates).

# Dutch (LB)

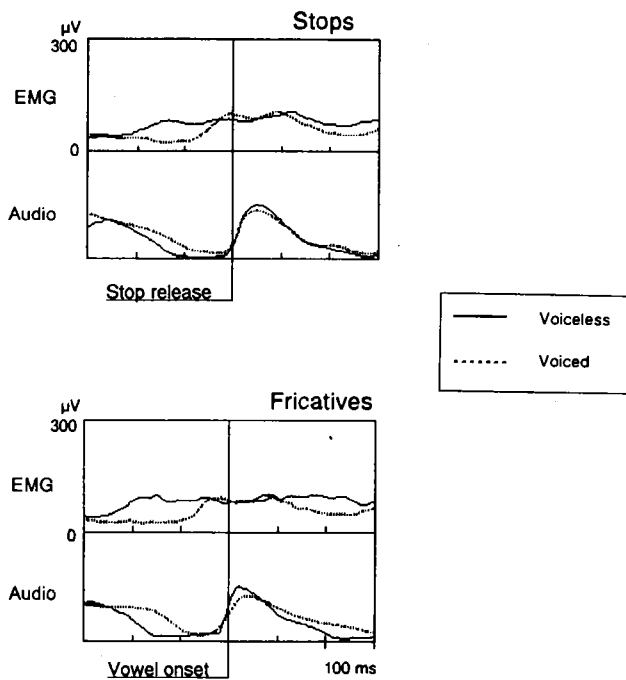


FIG. 3. Average EMG and audio signals for subject LB ( $n = 45$  for the stops and 29 for the fricatives).

fricatives. Average audio amplitude envelopes are also shown in Figs. 1–3. The audio envelope curves provide a rough indication of consonant/vowel boundaries, though it must be remembered that the tokens contributing to these averages displayed a range of temporal characteristics so that alignment of segment boundaries is imprecise except near the lineup point.

The plots of CT activity shown in Figs. 1–3 all share a common feature. In the left half of each figure, covering a period associated with the preceding vowel, the transition, and the consonant occlusion, the curves of voiced and voiceless consonants begin at the same level, diverge from each other with the voiceless one showing higher activity, and then reconverge in the vicinity of the lineup point. Qualitatively, where the curves have separated, they are clearly at visually distinct levels in all cases, except, perhaps, for the affricates of subject TB, shown in Fig. 1. The divergence of the two curves is due mostly to an increase of activity for the voiceless consonants; activity for the voiced consonants remains roughly constant, increasing later, so that, when the curves reconverge at the consonant release, they are at a higher level than for the preceding vowel, in accordance with the stress pattern of the utterance. The curves also appear to diverge in the right halves of each figure, for the following consonant, although the timing is more variable.

It is useful to consider the timing relationships in somewhat greater detail. For example, we consider the timing demonstrated in the top panel of Fig. 1, which shows the data for stops for subject TB. The audio envelope curves indicate that timing was similar for the voiced and voiceless consonants, since the curves follow about the same course except during the period associated with aspiration for the

voiceless consonants. The EMG levels are the same during the nucleus of the preceding vowel, but the curves begin to diverge shortly before the rapid descent of the audio envelope, which indicates the beginning of the transition period. The difference between the two EMG curves reaches its maximum about when the audio envelope curves approach the baseline, the point at which stop closure has been achieved for almost all tokens. The curves then approach each other again, meeting shortly after the lineup point; they are at essentially the same level through the following vowel, diverging again as the audio envelope begins its descent for the following consonant.

For fricatives, shown in the middle panel, a similar pattern is observed, though the pattern is a little less clear because the voiceless fricatives have longer durations than their voiced counterparts. Here, the EMG curves begin at the same level, during the preceding vowel. The curve for the voiceless consonant begins to increase almost immediately, however, shortly before the corresponding audio envelope begins its rapid descent. The maximum difference occurs when the audio envelope for the voiceless fricative nears its minimum, and the curves converge again, this time somewhat before the lineup point rather than after it, as in the upper panel. The curves diverge again from each other in the right half of the figure, at about the same place within the cycle for the voiceless consonants (i.e., at about the lead before the rapid descent of the audio envelope).

All the curves for the other two subjects, shown in Figs. 2 and 3, exhibit qualitatively the same type of behavior as Fig. 1. The EMG curves diverge roughly where the audio envelope for the voiceless consonant begins its rapid descent. The maximum difference between the two EMG curves occurs around occlusion for the voiceless consonant (although not so closely for the fricatives and affricates for subject NSM in Fig. 2), and the curves converge again in the vicinity of the lineup point. Subject NSM also differs somewhat from the other subjects in the right halves of the plots, in that the curves for voiced and voiceless consonants separate much earlier, during the vowel in the preceding (stressed) syllable. The results for subject LB in Fig. 3 shows the same timing of CT activity as those for subject TB in Fig. 1.

The difference in the EMG curves was tested quantitatively using the integrated “area under the curve” measure, described in Sec. I. Figure 4 shows the integrated value of cricothyroid activity averaged over all tokens for each condition. Standard deviations are also indicated. In all cases except one, the affricates for subject TB, the difference between the voiced and voiceless consonants is highly significant ( $p < 0.001$ ). For the affricates of subject TB, the difference was not statistically significant ( $t_{29} = 0.43, p > 0.5$ ).

The audio envelopes in Figs. 1–3 suggest that the vocal folds were vibrating for the voiced consonants produced by subjects NSM and LB. On the other hand, the voiced stops for subject TB in Fig. 1 would seem to have been produced at least partly devoiced. This can be deduced from the amplitude of the audio envelope during stop closure, which is almost similar for the voiced and voiceless cognates. The vibrations seem to stop during the later part of the oral closure for the voiced stops.

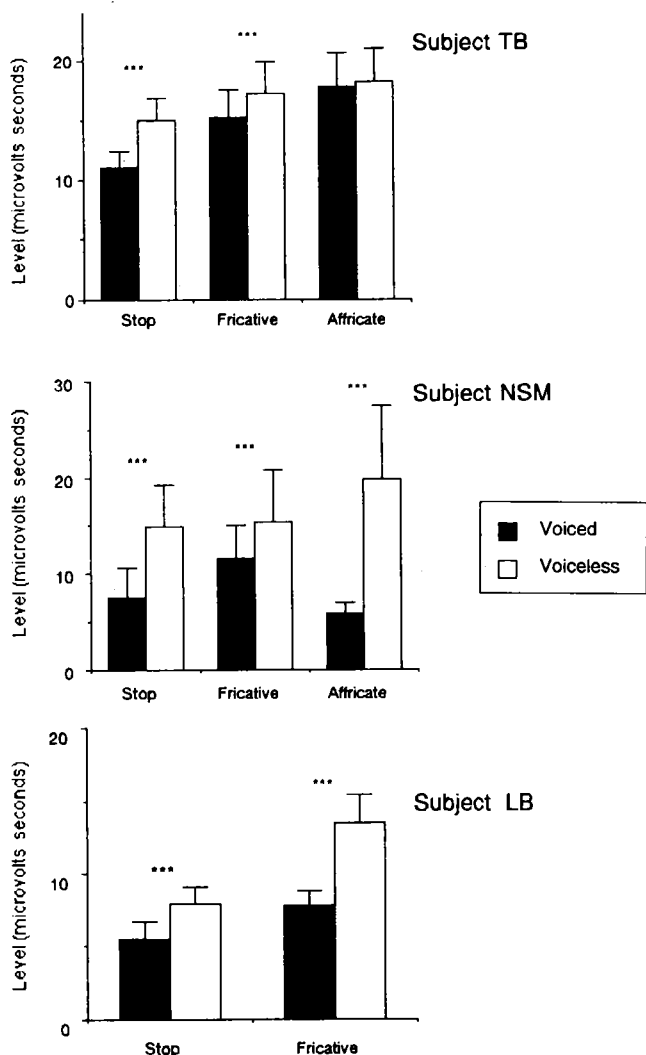


FIG. 4. Mean and standard deviation of cricothyroid activity level; \*\*\* indicates  $p < 0.001$ .

## B. Fundamental frequency

The measurements of fundamental frequency at the beginning of the vowel following the consonant are shown in Figs. 5–7 for the stops and fricatives for the three subjects and in Fig. 8 for the affricates. As expected, the  $F_0$  at this point of the vowel is higher after a voiceless consonant. In this voiceless context, the fundamental frequency generally starts at a high level and drops during the first periods. In the voiced context,  $F_0$  at the onset of the vowel is lower and may remain at the same level, rise, or even fall slightly. The difference in  $F_0$  following voiced and voiceless consonants was, in most cases, highly significant for all the ten periods measured. The only exception to this general trend consisted of the affricates for subject TB in Fig. 8. Here, the difference disappeared at pitch period number 7 ( $t_{28} = 1.26$ ,  $p > 0.1$ ) and also for the preceding pitch periods the difference was less robust. Recall that, for this speaker, the difference in cricothyroid activity between the voiced and voiceless affricates was not significant; cf. Figs. 1 and 4.

Overall, the consonant-induced variations in  $F_0$  appear to be less robust following affricates; cf. Fig. 8. As already

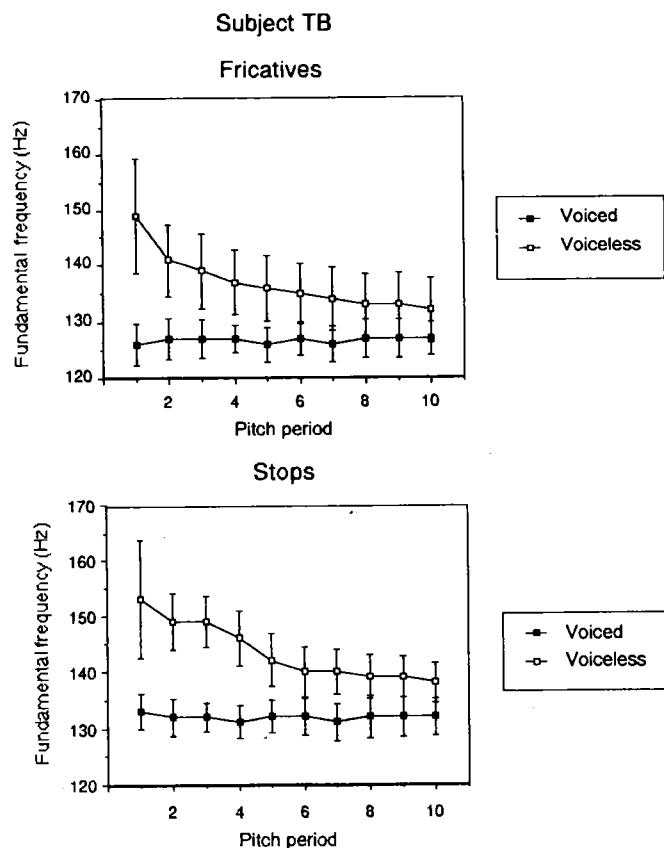


FIG. 5. Mean and standard deviation of  $F_0$  during the first ten pitch periods of the vowel following stops and fricatives for subject TB ( $n = 15$ ).

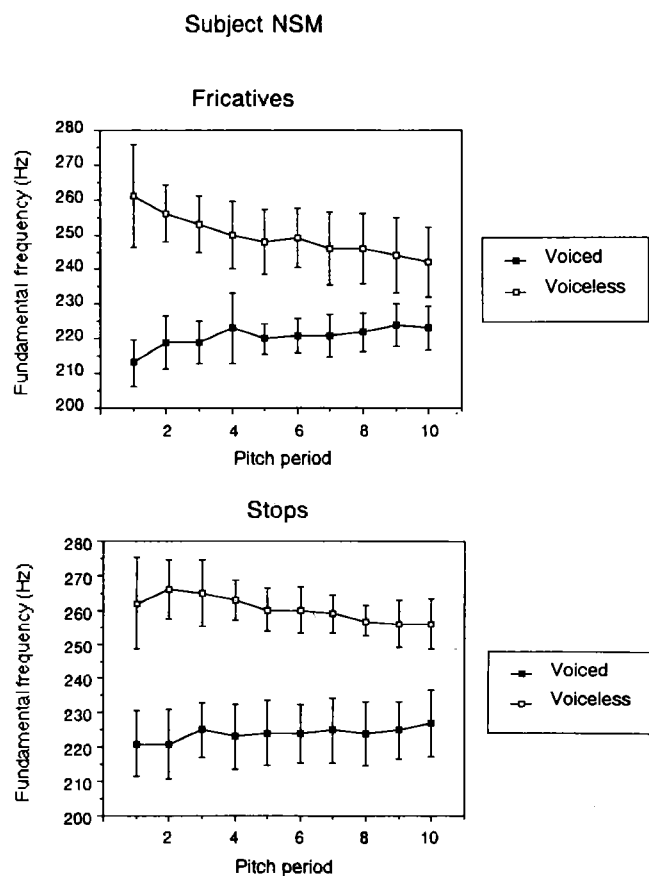


FIG. 6. Mean and standard deviation of  $F_0$  during the first ten pitch periods of the vowel following stops and fricatives for subject NSM ( $n = 15$ ).

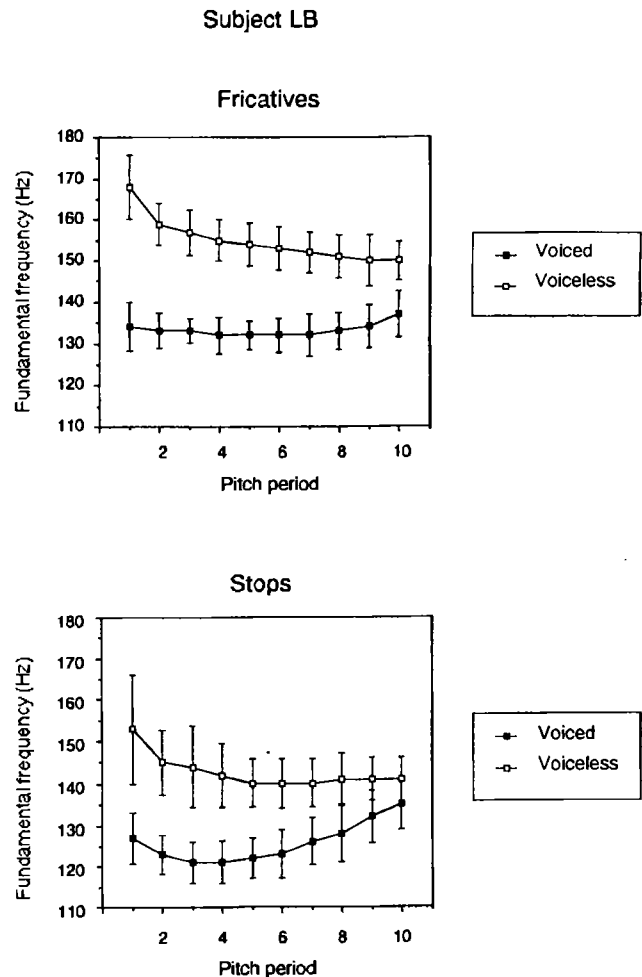
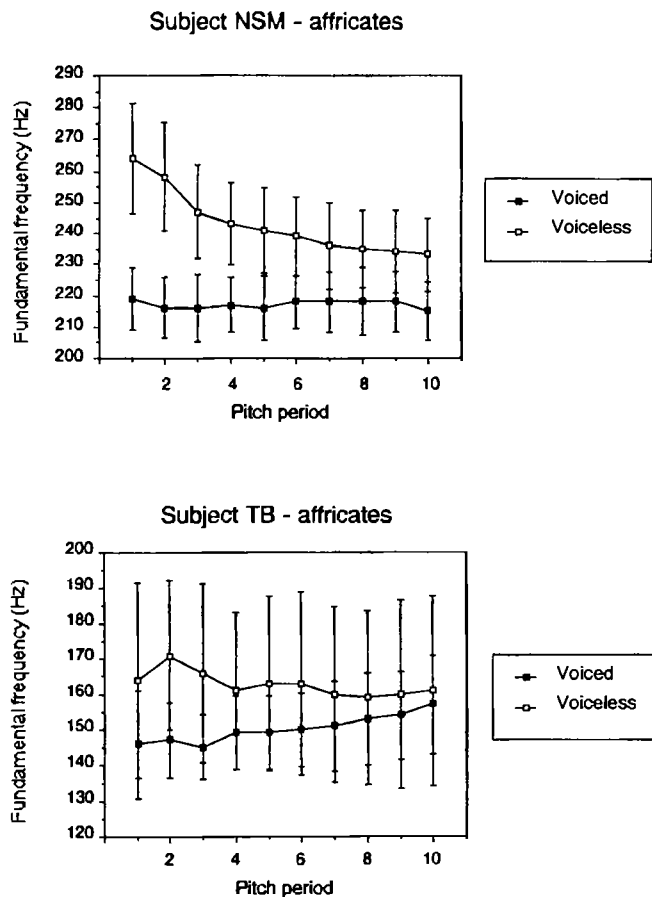


FIG. 7. Mean and standard deviation of  $F_0$  during the first ten pitch periods of the vowel following stops and fricatives for subject LB ( $n = 15$  and 10).

FIG. 8. Mean and standard deviation of  $F_0$  during the first ten pitch periods of the vowel following affricates for subjects NSM and TB ( $n = 10$  and 15, respectively).

noted, the difference disappeared at pitch period number 7 for subject TB. For subject NSM, the difference was highly significant for the first six pitch periods and significant for periods 7 through 10. It is evident, however, that for this subject, NSM, the absolute difference in Hz at the tenth period after the affricates is much smaller than at the same period following the stops and fricatives in Fig. 6. Furthermore, given the higher  $F_0$  of subject NSM, her tenth pitch period occurs approximately at the same point in time after vowel onset as pitch period number 7 of subject TB.

The relationship between the activity of the cricothyroid muscle during the consonant and the fundamental frequency at the beginning of the following vowel is illustrated in Fig. 9. This figure plots the average levels of the cricothyroid (cf. Fig. 4) against the  $F_0$  at the onset of the following vowel; the value of  $F_0$  represents the mean of the first three pitch periods. A positive relationship is found with Pearson product moment correlation coefficients of 0.64, 0.85, and 0.92 for subjects TB, NSM, and LB, respectively.

### III. DISCUSSION

The results of the present study show that the cricothyroid muscle increases its activity for voiceless consonants for all three subjects. This activity would act to increase the longitudinal tension of the cover of the vocal folds and should contribute to the inhibition of glottal vibrations. This was found for speakers of two languages with different stop

systems. In both American English and Dutch, the stops are either voiced or voiceless. However, the Dutch voiceless stops are unaspirated with a VOT of about 10–15 ms in the present study, while the American English voiceless stops are aspirated with a VOT of 60–80 ms (cf. Lisker and Abramson, 1964).

The present measurements of fundamental frequency at the beginning of the vowel following the voiced and voiceless

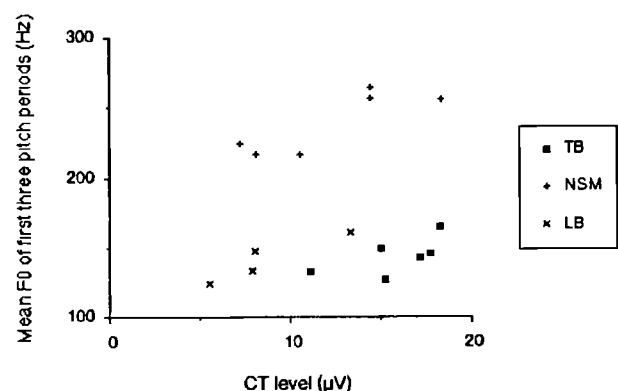


FIG. 9. Plot of cricothyroid activity level versus  $F_0$  at the beginning of the following vowel.

consonants are in good agreement with published results (cf. Ohde, 1984; Silverman, 1986). That is,  $F_0$  is higher after a voiceless than after a voiced consonant irrespective of the manner of production, namely, stop, fricative, or affricate. This is true also for the Dutch data in Fig. 7 where the voiceless stops are unaspirated; this has also been shown for French stops where the voiceless series is unaspirated (Fischer-Jørgensen, 1972). Similarly, Ohde (1984) found that the  $F_0$  of a vowel was similar if the preceding consonant was a voiceless aspirated or unaspirated stop. Thus it appears that the conditioning factor for the  $F_0$  difference is voicing and not aspiration. This conclusion is further strengthened by the fact that studies of  $F_0$  after voiceless aspirated and unaspirated stops have shown conflicting results where interspeaker and interlanguage differences seem to occur to a great extent (cf. Gandour, 1974; Hombert and Ladefoged, 1977; Jeel, 1975; Kagaya, 1974; Kagaya and Hirose, 1975; Zee, 1980). Presumably, aerodynamic factors are also involved. However, the results presented by Hutters (1984, 1985) suggest that the cricothyroid has a higher level of activity in Danish aspirated than unaspirated stops.

If there is thus a distinct difference in the level of  $F_0$  after voiced and voiceless consonants, the pattern of pitch change at the beginning of the vowel may differ. After voiceless consonants,  $F_0$  generally drops, although this is not clear for the vowels following stop consonants for subject NSM, cf. Fig. 6, or for those following affricates for subject TB; cf. Fig. 8. After voiced consonants, the fundamental frequency may either rise, fall, or stay level; all these three patterns can be found in Figs. 5–8. The  $F_0$  change at the beginning of the vowel thus depends not only on the preceding consonant but also on the overall intonation pattern of the utterance (cf. Silverman, 1986).

We thus argue that an increased longitudinal tension of the vocal folds is associated with voicelessness. The difference in tension between voiced and voiceless consonants is still manifest at the beginning of a following vowel, thus accounting for the commonly found consonant-induced variations in  $F_0$ , cf. Fig. 9 that shows a positive correlation between the cricothyroid activity during the consonant and the  $F_0$  level at the beginning of the following vowel. According to the present results, there is no clear difference in cricothyroid activity during the vowel following the consonant. If variations in cricothyroid activity are associated with the voicing distinction, they should occur at the transition between the vowel and the consonant, given the fact that the electrophysiological events lead the resulting mechanical effects with the latency depending on the contraction and relaxation time of the muscle. If CT activity were meant only to control  $F_0$  and not to contribute to devoicing, it might be expected to be initiated later relative to stop closure and fricative constriction. Although somewhat conflicting, studies by Baer (1981) and by Larson and Kempster (1985) of single motor units in the human cricothyroid muscle and by Atkinson (1978) of the EMG interference pattern during utterances with various intonation patterns indicate that the effective contraction time (actually the latency between EMG and the onset of pitch increase) is in the range of 20–80 ms, and relaxation times are somewhat longer than con-

traction times. The present results would also rationalize why the voicing status of a consonant appears to affect the fundamental frequency of a preceding vowel, independently from the prosodic structure of the utterance, to a lesser extent than it affects the following vowel.

While we would thus suggest that the well-attested  $F_0$  difference between vowels following voiced and unvoiced consonants is due to a change in vocal-fold tension caused by the cricothyroid muscle, it is obvious that other factors may also be involved. As reviewed by Hombert *et al.* (1979), these factors may include aerodynamic effects during stop closure and release and changes in the vertical position of the larynx that can affect the tension of vocal-fold tissues. While we have concentrated on the cricothyroid muscle, our reading of the literature suggests that the other adductor muscles of the larynx are suppressed for voiceless consonants; thus the body of the folds would be relaxed as the activity of the vocalis muscle decreases for voiceless consonants.

Kingston (1986) has suggested an alternate explanation for the consonant-voicing pitch effect. Analysis in different languages suggests that the pitch effect consistently accompanies the phonological voicing distinction, regardless of whether or not the vocal folds are actually vibrating. He suggests, then, that the pitch in the neighborhood of obstruents may be controlled independently as a cue to phonological voicing, rather than being a by-product of the gestures that control vibrations of the vocal folds and presence of aspiration. Although the present experiment did not specifically address this hypothesis, we would argue that the timing of increased CT activity for the voiceless consonants suggests that it is related to devoicing rather than to pitch control; if CT activity was only related to  $F_0$  control, the increase in activity should occur closer to the onset of the vowel following the consonant. Furthermore, the perceptual effectiveness of these  $F_0$  variations in cuing consonant voicing appears to be debatable (cf. Abramson and Lisker, 1985; Silverman, 1986).

Perhaps the most compelling evidence in favor of the line of reasoning that we have presented here is the finding for the affricates of subject TB. In this case, there is no significant difference in cricothyroid activity between the voiced and unvoiced cognates. Nor is the  $F_0$  difference in the following vowel clear-cut and robust in the context of the affricates. Taken together, these results, together with a review of the literature, suggest that control of laryngeal tension by means of the cricothyroid muscle is a mechanism that may be used to supplement abduction and reduction of transglottal flow as devoicing mechanisms. Though it is evidently not an essential component of the mechanism, there is converging evidence that it is used frequently, at least in prestressed position. The EMG curves suggest that the CT is also used to contribute to consonant devoicing in unstressed syllables, but further analyses are required to determine whether the timing relationships are similar to those for stressed syllables.

#### ACKNOWLEDGMENTS

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- Abramson, A., and Lisker, L. (1985). "Relative power of cues:  $F_0$  shift versus voice timing," in *Linguistic Phonetics*, edited by V. Fromkin (Academic, New York).
- Atkinson, J. (1978). "Correlation analysis of the physiological features controlling fundamental voice frequency," *J. Acoust. Soc. Am.* **63**, 211–222.
- Baer, T. (1981). "Investigation of the phonatory mechanism," in *Proceedings of the Conference on the Assessment of Vocal Pathology*, ASHA Rep. **11**, 38–46.
- Bell-Berti, F. (1975). "Control of cavity size for English voiced and voiceless stops," *J. Acoust. Soc. Am.* **57**, 456–464.
- Collier, R., Lisker, L., Hirose, H., and Ushijima, T. (1979). "Voicing in intervocalic stops and fricatives in Dutch," *J. Phon.* **7**, 357–373.
- Dixit, P., and McNeilage, P. (1980). "Cricothyroid activity and control of voicing in Hindi stops and affricates," *Phonetica* **37**, 397–406.
- Fisher-Jørgensen, E. (1972). "PTK et BDG français en position intervocalique accentuée," in *Papers in Linguistics and Phonetics to the Memory of Pierre Delattre*, edited by A. Valdman (Mouton, The Hague, The Netherlands), pp. 143–200.
- Fre Woldu, K. (1985). "The perception and production of Tigrinya stops," Reports from Uppsala University, Department of Linguistics **13**, 1–190.
- Gandour, J. (1974). "Consonant type and tone in Siamese," *J. Phon.* **2**, 337–350.
- Halle, M., and Stevens, K. (1971). "A note on laryngeal features," *Q. Prog. Rep. Res. Lab. Electron. MIT* **101**, 198–213.
- Hirose, H., and Gay, T. (1973). "Laryngeal control in vocal attack. An electromyographic study," *Folia Phoniatr.* **25**, 203–213.
- Hirose, H., and Niimi, S. (1987). "The relationship between glottal opening and the transglottal pressure differences during consonant production," in *Laryngeal Function in Phonation and Respiration*, edited by T. Baer, C. Sasaki, and K. S. Harris (College-Hill, Boston), pp. 381–390.
- Hirose, H., and Ushijima, T. (1978). "Laryngeal control for voicing distinction in Japanese consonant production," *Phonetica* **35**, 1–10.
- Hombert, J.-M., and Ladefoged, P. (1977). "The effect of aspiration on the fundamental frequency of the following vowel," *UCLA Work. Papers Phon.* **36**, 33–40.
- Hombert, J.-M., Ohala, J., and Ewan, W. (1979). "Phonetic explanations for the development of tones," *Language* **55**, 37–58.
- House, A., and Fairbanks, G. (1953). "The influence of consonantal environment upon the secondary acoustical characteristics of vowels," *J. Acoust. Soc. Am.* **25**, 105–113.
- Hutter, B. (1984). "Vocal fold adjustment in Danish voiceless obstruent production," *Ann. Rep., Institute of Phonetics, University of Copenhagen* **18**, 293–385.
- Hutters, B. (1985). "Vocal fold adjustment in aspirated and unaspirated stops in Danish," *Phonetica* **42**, 1–24.
- Jeel, V. (1975). "An investigation of the fundamental frequency of vowels after various Danish consonants, in particular stop consonants," *Ann. Rep., Institute of Phonetics, University of Copenhagen* **9**, 191–211.
- 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 analyses of Hindi stop consonants," *Ann. Bull., Research Institute of Logopedics and Phoniatrics, University of Tokyo* **9**, 27–46.
- Kingston, J. (1986). "Are  $F_0$  differences after stops accidental or deliberate?," *J. Acoust. Soc. Am. Suppl.* **1** **79**, S27.
- Larson, C., and Kempster, G. (1985). "Voice fundamental frequency changes following discharge of laryngeal motor units," in *Vocal Fold Physiology: Biomechanics, Acoustics and Phonatory Control*, edited by I. Titze and R. Scherer (The Denver Center for the Performing Arts, Denver, CO), pp. 91–103.
- Lehiste, I., and Peterson, G. (1961). "Some basic considerations in the analysis of intonation," *J. Acoust. Soc. Am.* **33**, 419–425.
- Lisker, L., and Abramson, A. (1964). "A cross-language study of voicing in initial stops: Acoustical measurements," *Word* **20**, 384–422.
- Löfqvist, A. (1980). "Interarticulator programming in stop production," *J. Phon.* **8**, 475–490.
- Löfqvist, A., and McGarr, N. S. (1987). "Laryngeal dynamics in voiceless consonant production," in *Laryngeal Function in Phonation and Respiration*, edited by T. Baer, C. Sasaki, and K. S. Harris (College-Hill, Boston), pp. 391–402.
- Löfqvist, A., McGarr, N. S., and Honda, K. (1984). "Laryngeal muscles and articulatory control," *J. Acoust. Soc. Am.* **76**, 951–954.
- Löfqvist, A., and Yoshioka, H. (1980). "Interarticulator programming in obstruent production," *Phonetica* **38**, 21–34.
- Löfqvist, A., and Yoshioka, H. (1984). "Intrasegmental timing: Laryngeal-oral coordination in voiceless consonant production," *Speech Commun.* **3**, 279–289.
- Minifie, F., Abbs, J., Tarlow, A., and Kwaterski, M. (1974). "EMG activity within the pharynx during speech production," *J. Speech Hear. Res.* **17**, 497–504.
- Ohde, R. (1984). "Fundamental frequency as an acoustic correlate of stop consonant voicing," *J. Acoust. Soc. Am.* **75**, 224–230.
- Perkell, J. (1976). "Responses to unexpected suddenly induced change in the state of the vocal tract," *Q. Prog. Rep., Res. Lab. Electron., MIT* **117**, 273–281.
- Sawashima, M., and Hirose, H. (1983). "Laryngeal gestures in speech production," in *The Production of Speech*, edited by P. MacNeilage (Springer, New York), pp. 11–38.
- Silverman, K. (1986). " $F_0$  segmental cues depend on intonation: The case of the rise after voiced stops," *Phonetica* **43**, 76–91.
- Sonesson, B. (1982). "Vocal fold kinesiology," in *Speech Motor Control*, edited by S. Grillner, B. Lindblom, J. Lubker, and A. Persson (Pergamon, Oxford), pp. 113–117.
- Stevens, K. (1977). "Physics of laryngeal behavior and larynx modes," *Phonetica* **34**, 264–279.
- Titze, I. (1980). "Comments on the myoeleastic-aerodynamic theory of phonation," *J. Speech Hear. Res.* **23**, 495–510.
- Titze, I. (1986). "Mean intraglottal pressure in vocal fold oscillation," *J. Phon.* **14**, 359–364.
- van den Berg, J. (1958). "Myoeleastic-aerodynamic theory of voice production," *J. Speech Hear. Res.* **1**, 227–244.
- Vencov, A. (1968). "A mechanism for production of voiced and voiceless intervocalic consonants," *Z. Phonet. Sprachwiss. Kommunikationsforsch.* **21**, 140–144.
- Westbury, J. (1983). "Enlargement of the supraglottal cavity and its relation to stop consonant voicing," *J. Acoust. Soc. Am.* **73**, 1322–1336.
- Yoshioka, H. (1981). "Laryngeal adjustments in the production of the fricative consonants and devoiced vowels in Japanese," *Phonetica* **38**, 236–251.
- Yoshioka, H. (1984). "Glottal area variation and supraglottal pressure change in voicing control," *Ann. Bull., Res. Institute of Logopedics and Phoniatrics, University of Tokyo* **18**, 45–59.
- Zee, E. (1980). "The effect of aspiration on the  $F_0$  of the following vowel in Cantonese," *UCLA Work. Papers Phon.* **49**, 90–97.