The Articulatory Implementation of the Breath-group and Prominence: Crico-thyroid Muscular Activity in Intonation.*

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Abstract. A theory has been proposed (Lieberman 1967) that accounts for some aspects of intonation in terms of two phonologic features, the breath-group and prominence. Acoustic and physiologic correlates of these features were derived by experimental procedures that made use of subglottal air pressure and flow measurements as well as acoustic analysis. Perceptual data indicated that listeners "decoded" certain intonational signals by means of 'motor theory perception' structured in terms of the 'archetypal', i.e., primary, articulatory correlates of these features. In the present study this theory was tested by recording the electrical activity of the crico-thyroid muscle of the larynx for a set of 480 short statements and yes-no questions that sometimes had non-terminal +prominent syllables. Independently derived data of Fromkin and Ohala (1968) also were examined. The data were consistent with the theory proposed by Lieberman (1967) except that +prominent syllables in unmarked breath-groups had crico-thyroid activity. In yes-no questions where the crico-thyroid was active at the end of the marked breath-group, non-terminal +prominent syllables had no crico-thyroid activity. The archetypal articulatory correlate of the marked breath-group is an increase in laryngeal tension, whereas the archetypal articulatory correlate of +prominence is an increase in subglottal air pressure. Implementation rules relate the phonologic features to their archetypal and secondary articulatory correlates.

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In a recent study (Lieberman 1967) some linguistic aspects of intonation were analyzed in terms of two phonologic features, the breath-group and prominence. These features were defined in terms of their acoustic and physiologic correlates. Phonologic features may be regarded as psychological constructs that reflect the constraints of both the human speech producing apparatus and auditory perception (Lieberman 1969). Some phonologic features are closely related to an articulatory maneuver that involves a specific muscle. For example, the feature nasality at the articulatory level is physically effected by means of the levator palatini muscle which closes or opens the nasal cavity to the rest of the vocal tract. However, many phonologic features can not be related in an invariant manner to an articulatory maneuver that involves a particular muscle, muscle group, or anatomical structure. The phonologic feature stop, for example, can be effected by means of any one of a number of articulatory maneuvers. The condition +stop at the articulatory level must be regarded as a "state" function, i.e., a state of occlusion in the oral vocal tract.

Other features must also be regarded as state functions at the articulatory level. The prosodic features voicing, prominence, and the breath-group each involve the coordinated activity of many muscles, and under different conditions, different muscles may be involved in the implementation of a given feature. Indeed, the human larynx is so constructed that the fundamental frequency of phonation is a function of both the transglottal air pressure drop and the tensions of the laryngeal muscles (Muller 1848, pp. 1000-15; Van den Berg 1960; Ladefoged 1962; Flanagan and Landgraf 1968; Lieberman 1967; Lieberman et al. 1969). In the absence of any information save that contained in the acoustic signal, it would appear to be difficult to ascertain whether a change in fundamental frequency is due to a change
in the tension of the laryngeal muscles or a change in the sub-
glottal air pressure. That is to say, there are two different
mechanisms, laryngeal and subglottal respiratory maneuvers, that
can produce similar changes in fundamental frequency. However,
under certain conditions, listeners appear to "decode" intona-
tional signals in terms of the articulatory mechanisms that
could underlie the acoustic signal (Lieberman 1967). The lis-
teners, in other words, appear to be acting as though they make
use of a "motor theory" of speech perception to interpret the
acoustic signal. It is important to note at this point that a
"motor theory" of speech perception does not mean that listeners
consciously or unconsciously mimic the sounds that they hear,
nor does it even imply that the listeners actually "compute" the
acoustic effects of various articulatory maneuvers using a tech-
nique of "analysis-by-synthesis" (Halle and Stevens 1959).

A "motor theory" of speech perception, in the sense that
we will use the term, simply states that the perceptual recogni-
tion routines that are used when speech is decoded are structured
in terms of the constraints of the human vocal apparatus. Thus,
just as a particular species of frog has auditory receptors that
respond to the spectrum of that species' mating croak (Capranica
1965), humans apparently have a perceptual mechanism that res-
ponds to the formant transitions of the stops /b/, /d/, /g/
(Lieberman et al. 1967).

We still have not answered the apparent paradox that seems
to apply to a "motor theory" mode of perception for intonation.
If alternate articulatory mechanisms can produce the same funda-
mental frequency variations, how can listeners decode the in-
tonational signal in terms of the underlying articulatory maneu-
vers? The solution proposed (Lieberman 1967) was that the lis-
teners decode in terms of the "archetypal" pattern of articula-
tory activity. The archetypal pattern was defined as the
simplest or basic state of muscular control that would produce the intonational signal. The hypothetical archetypal normal breath-group was said to involve a state of minimal laryngeal control throughout expiration so that changes in fundamental frequency (excluding those due to mechanical and aerodynamic interactions with the rest of the vocal tract) would follow from changes in transglottal air pressure. The fundamental frequency of phonation would thus rapidly fall at the end of a breath-group where the subglottal air pressure must change from a positive to a negative pressure in order to get air into the lungs during inspiration. The normal breath-group thus would be the basis of the intonation contour transcribed by Jones (1932) and Armstrong and Ward (1926) as Tune I, by Pike (1945) as the 'pause' / , and by Trager and Smith (1951) as 231#. The data presented by Lieberman (1967) showed that some adult speakers used the archetypal pattern of articulatory activity to produce these intonational signals. It was not possible at the time to measure the electrical activity of the laryngeal muscles. Laryngeal maneuvers thus had to be inferred from measures of subglottal air pressure, lung volume, and the acoustic signal.

These data further indicated that the marked breath-group (+ breath-group) involved a change in laryngeal tension at the end of the breath-group which offset the falling subglottal air pressure to produce either a rising or level terminal fundamental frequency contour. The marked breath-group appeared to be the basis for the signals that have been transcribed as Tune II by Jones (1932) and Armstrong and Ward (1926), as the 'pause' / by Pike (1945) and as either 232/ or 232// by Trager and Smith (1951). The acoustic correlates of the phonologic feature

1The phonetic distinction between the terminals / and // may be a coarticulation effect. When a speaker uses a +breath-group in
prominence included duration, fundamental frequency, and intensity (Fry 1955; Lieberman 1960). The identifiable articulatory correlates included increasing the duration of a segment and increasing the subglottal air pressure (Ladefoged 1962).

The analysis of intonation presented in Lieberman (1967) also was consistent with the notion of "motor theory" decoding (Liberman et al. 1967) of certain intonation contours, in particular of +breath-groups that had a non-terminal +prominent syllable. Note that the two intonation contours that are schematized in Fig. 1 have different terminal rises. The listeners, in a carefully controlled psychoacoustic experiment (Hadding-Koch and Studdert-Kennedy 1964), said that both of these contours had the same terminal rise. The listeners obviously were not merely responding to the physically present fundamental frequency signal. They instead appeared to be evaluating the terminal fundamental frequency contours in terms of the degree of laryngeal tension that would be present in natural speech. They also appeared to be interpreting the non-terminal fundamental frequency peaks as though they were a consequence of a peak in the subglottal air pressure function (Ladefoged 1962). The listeners also appeared to "know" that a non-terminal peak in the subglottal air pressure function will result in a lower subglottal air pressure at the end of the breath-group. This "air pressure perturbation" hypothesis is, of course, part of this theory for the production

Footnote 1 cont'd. a non-sentence-final position, he may not complete the tensioning of his laryngeal muscles at the end of the +breath-group's because he must rapidly begin to relax these muscles for the beginning of the breath-group that follows. Similar effects occur for other phonologic features; see Lindblom (1963) for a careful study of coarticulation effects in vowels.
and perception of intonation. Note that the intonation contour in Fig. 1 that had the greater non-terminal peak fundamental frequency has the smaller terminal fundamental frequency. Since the lower contour had a higher non-terminal peak $f_0$, a greater non-terminal peak subglottal air pressure would have been employed than would have been the case for the upper contour. This would result in a lower subglottal air pressure at the end of the breath-group for the lower contour and an equivalent degree of laryngeal tension would thus result in a lower terminal fundamental frequency.

The listener's perceptual recognition routine for intonation, in other words, "knows" that:

a. terminal non-falling fundamental frequency contours are the result of increases in laryngeal tension,

b. non-terminal fundamental frequency peaks--at least in marked breath-groups--are the result of a momentary increase in subglottal air pressure,

c. the presence of a non-terminal peak in subglottal air pressure will result in a lower terminal subglottal air pressure than would be the case if the non-terminal peak were absent,

d. the listener also "knows" that all these maneuvers modify an archetypal normal breath-group.

The theory that we have briefly summarized is fairly complex, though it is no more complex than the theory that we must propose for the perception of the stop consonants (Liberman, et al. 1967). We have said that phonologic features may have complex articulatory correlates and we have further stated that complex perceptual recognition routines are involved in decoding of the acoustic signal in terms of the articulatory correlates of these features.

Recent papers by Ohala and Hiranu (1967), Vanderslice (1967), Fromkin and Ohala (1968) and a review by Kim (1968) dispute both
the general nature of the phonologic features that we have proposed and the specific correlates of the archetypal breath-group and prominence that we have discussed, as well as the status of perception structured in terms of the constraints of speech production, i.e. the "motor theory" of speech perception. We will present some new electromyographic data obtained from laryngeal and supralaryngeal muscles during speech. These data are relevant both to the general question of the relationship between a phonologic feature and a particular muscular maneuver and the specific question of the status of the analysis of intonation proposed by Lieberman (1967). We will also discuss the data presented by Fromkin and Ohala (1968) which is consistent with, and which complements, our new data.

Experimental data. Electromyographic data were obtained from the crico-thyroid and orbicularis muscles of a female speaker of American-English (KSH). Concentric needle electrodes were inserted into these muscles and the electrical muscle potentials were amplified and recorded on a multi-channel magnetic tape recorder while they were being monitored on a Grass Instruments oscillograph. The speaker throughout this experiment spoke short sentences like:

It is pattering.
Is it pattering?
It is pattering.
Is it pattering?

[The italics (or underlines) indicate emphasis.]

The words "pattering, packer, parfait, keeper, and recap" were produced in unemphasized declarative sentences, unemphasized yes-no questions and in declarative and yes-no questions with emphasis. The speaker read a list in which these sentences appeared in a random order until each sentence was uttered
twenty times; 480 utterances were thus recorded. A computer
program was then used which averaged the electromyographic sig-
nals for each group of twenty tokens of each sentence, excluding
those few tokens of each utterance which were faulty in various
ways. The computer program 'lined up' each sentence in terms of
the cessation of phonation. The end of phonation for each sen-
tence was determined from the acoustic signal which was simul-
taneously recorded on both the magnetic tape and the oscillogram.

In Fig. 2a we have presented the integrated and averaged
 electromyographic data for the sentence "It is pattering". The
integral of the action potentials of a muscle is a valid measure
of muscular activity. The averaging technique, which averages
a number of examples of the same linguistic construct, lessens
the possibility of artifact influence on our conclusions. In
this case, 20 tokens of the sentence were averaged together.
The activity of the orbicularis muscle is plotted in 'X' symbols
while the activity of the crico-thyroid muscle is plotted in
solid dots. The vertical, ordinate scale on the graph is the
electrical activity of the muscles in microvolts. Time is plotted
on the horizontal axis in milliseconds. The negative and
positive values of time refer to the computer 'line up' point.

In Fig. 2b, the fundamental frequency of phonation has been
averaged for six of the above utterances, and plotted on the
same time scale. The fundamental frequency was measured on
narrow band spectrograms by tracking the fifth harmonic of the
fundamental.

Note that the electrical activity of the orbicularis muscle
is limited to a single peak centered on $t = -650$ msec. This
peak corresponds to the closure of the lips for /p/, as we can
see by referring to the fundamental frequency contour in Fig. 2b
which bears a phonetic transcription of the utterance. Note
that no electrical activity occurs in the crico-thyroid muscle
at the end of the sentence \( t = 0 \) msec.). A small (50 microvolt) peak in crico-thyroid activity does occur at \( t = -550 \) msec. This peak corresponds with the primary lexical stress of the word 'pattering'.

In Fig. 3a similar data are plotted for the sentence "Is it pattering?" Note that a peak in the orbicularis channel still occurs. Note that, in contrast to Fig. 2a, electrical activity occurs in the crico-thyroid muscle at the end of the sentence. The activity of the crico-thyroid muscle results in an increase in the fundamental frequency of phonation (Muller 1848; Van den Berg 1960; Ohala and Hirau 1967; Ohman 1967).

In Fig. 3b the fundamental frequency of phonation has been averaged for six of the above utterances and plotted on the same time scale. Note that the fundamental frequency also rises at the end of the breath-group. Examination of the data for all of the sentences showed that the increase in the electrical activity of the crico-thyroid muscle and the increase in the fundamental frequency occurred at the end of the marked breath-group, irrespective of the number of syllables in the final word of the sentence or their lexical stress. In Fig. 4 averaged electromyographic data is presented for five marked breath-groups. Note that the activity of the crico-thyroid is similar for all the questions. The change in stress pattern and the number of syllables have no effect on the observed crico-thyroid activity.

In Fig. 5a electromyographic data is presented for the word "pattering", with overstress, in the sentence 'It is pattering'. Note the presence of crico-thyroid activity centered at -600 msec. Note the absence of crico-thyroid activity at the end of the breath-group. In Fig. 5b electromyographic data is presented for "pattering" as it occurred when it was overstressed in a marked breath-group, i.e., in the sentence 'Is it pattering?' Note the presence of crico-thyroid activity at the end of the
breath-group and the relative absence of crico-thyroid activity at -600 msec. Our acoustic analysis of the sentences plotted in Fig. 5 revealed that the emphasis placed on the word "pattering" was manifested by the acoustic correlates of the phonetic feature prominence that have been described by Jones (1932), Fry (1955), Lieberman (1960) and others. The duration of the vowels of "pattering" were greater when it was marked by prominence and the fundamental frequency of the first vowel was always greater for the +prominent examples. We did not measure the intensity of the speech signal, but in all likelihood, it was probably somewhat greater for the +prominent examples.

Discussion. Let us summarize the observations that we have drawn from this experimental data. About 480 short sentences that were uttered by a single speaker were analyzed. Some of these sentences were yes-no questions that were produced by means of a marked breath-group. Some of the sentences had words that the speaker was asked to emphasize. The sentences with emphasized words had non-terminal +prominent syllables. The data showed that:

1. The unmarked breath-groups terminated with a falling $f_0$ contour and there was no crico-thyroid activity at the end of these breath-groups.

2. The marked breath-groups were always terminated by a rising $f_0$ contour that was produced by means of increased tension of the crico-thyroid muscle.

3. When a syllable was marked by means of +prominence in an unmarked breath-group it had a higher $f_0$ and there was increased activity of the crico-thyroid muscle that was correlated with the particular syllable.

4. When a syllable was marked with +prominence in a marked breath-group it also had a higher $f_0$. However, no increase
in crico-thyroid muscle activity could be correlated with the $f_0$ prominence of the syllable.

(5) Some crico-thyroid activity could be correlated with primary lexical stress in an unmarked breath-group. However the magnitude of this crico-thyroid activity was 50 percent smaller than was the case for the +prominent syllables that occurred in unmarked breath-groups. No crico-thyroid activity could be associated with lexical stress in marked breath-groups.

Our interpretation of this data is that the primary, i.e., archetypal articulatory correlate of the +breath-group is an increase in crico-thyroid muscular activity (and possibly other synergetic laryngeal muscular activity\(^2\)). In contrast, the archetypal correlate of +prominence is an increase in subglottal air pressure\(^3\). In an unmarked breath-group, where the speaker is not going to do anything with his crico-thyroid muscle at the end of the breath-group, he may use it to manifest +prominence together with increased subglottal air pressure. In a +breath-group the crico-thyroid muscle is "reserved" to implement the

\(^2\)There is some evidence that indicates that the laryngeal muscles must act in concert to effect changes in fundamental frequency (Van den Berg 1960; Ohala and Hirano 1967).

\(^3\)Ladefoged (1968) notes that subglottal respiratory activity is always correlated with prominence in his data whereas other articulatory maneuvers are not. Ladefoged (personal communication) would make subglottal activity a necessary articulatory correlate of prominence. This is, of course, a stronger claim than stating that subglottal activity is the archetypal articulatory correlate of prominence. However, in either case laryngeal maneuvers are secondary articulatory correlates of prominence. The secondary articulatory correlates all appear to involve increased muscular activity (Lieberman 1969).
terminal $f_o$ contour and the speaker thus uses only an increase in
subglottal air pressure to implement the non-terminal +prominence.
The speaker may perhaps use less air pressure for a +prominence
that occurs in a - breath-group where he can use laryngeal maneuv-
ners to implement the +prominence in addition to the air pressure
peak. These data are, of course, consistent with the analysis-by
synthesis motor theory model proposed in Lieberman (1967). The lis-
teners in the Hadding-Koch and Studdert-Kennedy (1964) psychoacous-
tic experiment appeared to decode the intonational signals as
though prominence was caused by a subglottal air pressure peak.
The data are, moreover, consistent with the electromyographic data
that have been published by Fromkin and Ohala (1968).

We have reproduced some of the Fromkin and Ohala (1968) data
in Figs. 6 and 7. We have taken the liberty of marking the col-
umns of these figures since it will make the discussion easier to
follow. First note the data in column A of Fig. 6. The first
graph of this column is a plot of the fundamental frequency of
the utterance, "Bev bombed Bob". The second graph plots the sub-
glottal air pressure which was measured by means of a tracheal
catheter. The third graph is a plot of the unintegrated electro-
myographic signal from the crico-thyroid muscle. The electrical
activity of the muscle shows up as a series of 'spikes'. The
activity of the lateral crico-arytenoid muscle is plotted in the
fourth graph. The lateral crico-arytenoid is used to adduct the
vocal cords and to apply medial compression (Van den Berg 1960).
In order for phonation to take place, the vocal cords must be
adducted from their open, respiratory position. The fifth graph
is a plot of the acoustic signal while the bottom graph is a
timing pulse that indicates an interval of 100 msec.

Note that the lateral crico-arytenoid muscle (the fourth
graph in Fig. 6a) is firing both before and after the subglottal
air pressure builds up and decays. The subglottal air pressure

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curve thus would appear to reflect subglottal articulatory maneuvers. The entire utterance is voiced so we should expect no perturbations in the $f_o$ function that were due to opening and closing the glottis for voiced-voiceless distinctions. Note that the $f_o$ contour, if it is traced and superimposed on the $P_s$ contour is remarkably similar to the latter. There are falls in $f_o$ before voiced obstruents but these falls are due to the supralaryngeal obstruction which, of course, reduces the transglottal air flow (Ohman 1967). This is indeed a better example of a speaker who employs the archetypal articulatory correlates of the unmarked breath-group than any example in Lieberman (1967). The clever use of voiced phonetic material by Fromkin and Ohala removed perturbations of $f_o$ that may result from the "setting and resetting" of laryngeal tension that must occur when voiced-voiceless distinctions occur (Lieberman 1968). The particular phonetic material which does not involve vowels with low first formants also removes one source of interaction between the supralaryngeal vocal tract and the larynx (Flanagan and Landgraf 1968). Note, the similarity of the entire $P_s$ and the non-terminal $f_o$ function for utterance $E$ of Fig. 7.

In utterances $6B$, $C$ and $D$ +prominence is manifested by means of both subglottal air pressure and crico-thyroid activity. In utterances $7E$ and $F$ the terminal $f_o$ contours of the marked breath-group are also due to crico-thyroid activity as is the case for utterances $G$ and $H$. However note that the increase in crico-thyroid activity in $G$ and $H$ occurs about 200 msec after the peak in $P_s$ which is coincident with the marked $f_o$ prominences. Note too that these air pressure peaks are substantially greater than those that occur in utterances $B$, $C$, and $D$. Note too, that the "air pressure perturbation" effect discussed by Lieberman (1967) is evidenced by these data. Compare the terminal air pressures of
utterances G and H with F and E. The air pressure is lower (by about 2.5 cm, though it's hard to read the compressed scale accurately) at the end of utterances G and H. This follows from the probable programming of the respiratory system for a breath-group (C.F. Lieberman 1967; 54, 71 and 98-100).

**Phonologic features and articulatory maneuvers.** The data that we have discussed clearly demonstrate that phonologic features and articulatory maneuvers can not be mapped in an invariant one-to-one manner. The feature *prominence* involved activity of the crico-thyroid muscle only when the speakers "knew" that they would not be using this muscle at the end of a +breath-group. The implementation rules of the phonetic component that relate the phonologic feature *prominence* to the articulatory output thus must note whether a segment marked *prominent* occurs in a +breath-group. The implementation rule, in other words, will assign different muscular maneuvers to the state *prominent* in different contexts. Of course there is nothing particularly novel in this concept. The phonologic feature *stop* will have very different articulatory correlates for labial and glottal stops. Phonologic features, in general, appear to be "state" functions insofar as the physical invariance in each feature is a "state" of the articulatory apparatus, e.g., an oral vocal tract occlusion for *stop*, or the state of phonation or incipient phonation for *voicing* (Lieberman, 1969). It is only in certain cases like *nasal* that an invariant articulatory maneuver can be assigned to a particular feature.

The implementation rules that assign laryngeal maneuvers to *prominence* are, however, of particular interest since they must take into account articulatory events that may take place several syllables after the *prominent* syllable. Lashley (1951) stated that associative theories can not account for processes like the
production of phonetic sequences of speech. Wickelgren (1969) in a recent paper proposed that speech could be encoded by means of associations between context-sensitive elementary motor responses. The word "stop" would thus be encoded "allophonically" as /s, t, s, o, t, o, p/ rather than being coded "phonemically" as /s, t, o, p/. Wickelgren's theory of course requires a greater 'memory' in which context sensitive allophones would be stored. The memory requirements are however plausible in terms of human mental capacity so long as only the immediate context of each allophone must be considered. Effects like the manifestations of crico-thyroid muscular activity in *prominent* syllables which involve the "remote" context of the *prominent* syllable argue against Wickelgren's context-sensitive allophonic encoding of speech. The memory requirements would preclude simple associative encoding.

Archetypal articulatory correlates. The data that we have been discussing suggest how the archetypal or primary articulatory correlates of phonologic features may be manifested. The articulatory bases of the phonologic feature *prominence* must obviously include laryngeal maneuvers. The archetypal articulatory correlate of *prominence*, however, appears to be a peak in subglottal air pressure (Ladefoged 1962; Lieberman 1967; Ladefoged 1968). The data support, in detail, the analysis proposed in Lieberman (1967) if prominence is regarded as a state function (Lieberman 1969). The data also support the "motor theory" decoding of intonational signals that is proposed in Lieberman (1967).

Other prosodic features. The analysis proposed in Lieberman (1967) is limited to only two prosodic features, the breath-group and prominence. It is apparent that other prosodic features also must be considered in order to account for phenomena like the accent system of Swedish (Ohman 1967) or the tone systems
that occur in many languages (Wang 1967). Still other features may be necessary to account for the abrupt fundamental frequency falls that serve as phonetic manifestations of contrast and emphasis in English (Bolinger 1958). Some of the data that we presented in the present study, for example, the crico-thyroid activity that was associated with lexical stress in the unmarked breath-groups, may be articulatory manifestations of features like those proposed by Bolinger, Ohman and Wang. The data of Fromkin and Ohala (1968) also show muscular activity that may reflect the presence of features other than the breath-group and prominence. There also may be complex interactions between these unspecified features and the breath-group and prominence. Further experiments and theoretical refinements are obviously necessary. However, the data that we have discussed are consistent with the framework for the analysis of intonation that we have proposed and indicate that we may be going in the right direction.
Figure 1

Two fundamental frequency contours that listeners identified as having the "same" terminal fundamental frequency rise (from Hadding-Koch and Studdert-Kennedy 1964).
Figure 2

Averaged electrical activity of the orbicularis and crico-thyroid muscles (a) and fundamental frequency (b) for the sentence, It is pattering. Note that the crico-thyroid muscle, which effects fundamental frequency changes, is not active at the end of the sentence (t = 0).
FIG. 2A

A

EMG

Potential in μv

-800
0
100

Crico thyroid
Orbicularis

B

Average Fundamental Frequency

f₀

-800
-600
-400
-200
0
100

Time in msec.

It I l z p æ t æ In
Figure 3

Averaged electrical activity of the orbicularis and crico-thyroid muscles (a) and fundamental frequency (b) for the sentence, Is it pattering? Note that the crico-thyroid muscle is active at the end of the sentence (t = 0).
Crico-thyroid activity for five sentences (approximately 20 tokens per average) that each had the form, Is it pattering?, Is it a packer?, etc. All of the sentences have been 'lined up' with respect to the end of phonation (t = 0). Note that the increase in crico-thyroid activity always occurs approximately 200 msec before the end of phonation, independent of the number of syllables in the final word of the sentence.
Figure 5

Averaged electrical activity of the orbicularis and crico-thyroid muscles for the sentences (a) It is pat ter ing, and (b) Is it pattering? Emphasis was placed on the word pattering in both the declarative and the yes-no questions. Note that a peak in crico-thyroid activity is evident centered at $t = -600$ msec in (a) whereas no non-terminal peak occurs in (b) where the crico-thyroid is active at the end of the marked breath-group.
Figure 6

Electromyographic, physiologic, and acoustic data from Fromkin and Ohala (1968).
Electromyographic, physiologic, and acoustic data from Fromkin and Ohala (1968).
References


Muller, Johannes. 1848. *The Physiology of the Senses, Voice and Muscular Motion with the Mental Faculties*, W. Baly, translator, London. Walton and Maberly.


