LARYNGEAL BOUNDARY SIGNALS

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In this report we shall study how a variation in morpheme boundary location may affect the behaviour of some laryngeal muscles (vocalis m, cricothyroid m, and sternohyoid m). The activity of the muscles was recorded in an EMG investigation carried out at the Research Institute of Logopedics and Phoniatrics in Tokyo during the fall of 1969.[1] The present data are derived from a speech sample which was composed chiefly to investigate how the selected muscles participate in the production of Swedish word tones. A preliminary report of the word tone data (Gårding et al., 1970) was published in the Annual Bulletin No. 4. The same bulletin contains reports on a number of other experiments all of which aim at exploring the functioning of laryngeal muscles during speech (Hirose et al., Simada and Hirose, Ohala and Hirose, 1970).

MORPHEME BOUNDARIES AND SYLLABLE BOUNDARIES

Acoustic and perceptual aspects of morpheme and syllable boundaries were studied rather extensively in Swedish material (Gårding, 1967).

A spectrographic analysis of pairs of sequences that differ in the location of a morpheme boundary (e.g. tåg-ångare, "train-ferry", and tå-gångare, "toe-walker") showed that the acoustic segments around the boundary depend on the structure of the underlying morphemes, the stress pattern of

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[1] I wish to thank my collaborators at the Institute of Logopedics and Phoniatrics for their invaluable aid. I am particularly indebted to Doctors O. Fujimura, H. Hirose, and Z. Simada. I have also profited from some comments from Doctor M. Sawashima.

the phrase and the rate of utterance of the speaker. Between stressed syllables the speaker can time and arrange his speech gestures in different ways. The phonetic result was called internal juncture, a marked boundary. By means of perceptual tests it could be shown that listeners react to these differences particulary if they are accompanied by a change in the feature composition (aspiration, glottal stop etc.) of the segments involved. The spectrographic study also **brought** out some common characteristics by which speakers realize morpheme boundaries in varying phonetic environments. The location of the boundary can in most cases be related to an interval of low intensity in the spectrogram. From a study of the formant movements it could also be inferred that the speech organs slow down and move toward a neutral position in connection with the marked boundary. When the second morpheme starts with a vowel, the airstream is checked by a glottal closure or constriction (various manifestations of glottal stops appear in the spectrograms). In a sequence in which the second morpheme has a consonantal beginning there is no spectral indication of a glottal closure. However, the initial consonant closure or constriction is typically prolonged by a time interval comparable to that of the glottal closure.

With an increased rate of utterance speakers change their articulation in a uniform manner. One of the stressed syllables is reduced, the prolonged closure or constriction interval disappears and the intervocalic consonants are rearranged in such a way that as many as possible become syllable initial. This was interpreted as an adjustment on the part of the speaker to the general syllabification patterns (the unmarked boundaries) of the language. The process can be seen as the result of a shift to a simpler production program. In an informal test speakers appeared to have surprisingly similar notions of the syllable boundary locations for which rules could be set up. Perceptual tests showed that when boundaries followed these rules the morpheme division made by listeners tended to become haphazard. For example, a syllabification like *tå-gångare* in rapid speech could be interpreted as meaning both *train-ferry* and *toe-walker*.

MATERIAL

The present material was composed in such a way that it will be possible to study the effect of moving the morpheme boundary in a sequence from ...V + CV... to ...VC + V... and the effect of replacing a morpheme boundary ...V + CV... by a syllable boundary ...V - CV...

Test words

Orthographic representation with hyphens to show constituents	Modified IPA transcription
(1) mån-år or må-når	[ˇmo:no:r]
(2) må-når	[ˇmo:ˋno:r]
(3) mån-år	[ˇmo:nˋo:r]
(4) *må-når*	[ˇmo:ˈno:r]
(5) *mån-år*	[ˇmo:nˈo:r]
(6) tå-gångare or tåg-ångare	[ˇto:gɔnaˋrɛ]
(7) tå-gångare	[ˇto:ˋgɔnarɛ]
(8) tåg-ångare	[ˇto:gˋɔnarɛ]

The transcription follows the IPA principles according to which /ˈ/ indicates strong stress with the acute (simple) tone and /ˇ/ marks the stressed syllables of words with the grave (compound) tone. When two or more syllables follow the stress, the syllable bearing the second element of the compound tone is marked by /ˋ/. In the emphatic utterances (4) and (5), underlined in the orthographic representation, /ˋ/ is replaced by strong stress /ˈ/.

The test words are compound nouns made up of Swedish morphemes. Number (4) is contrived and specially designed for the experiment. Conforming to the rules for compound formation, the stressed syllable of the first element carries the grave accent /ˇ/.

Items (1) and (6) are meant to exemplify a pronunciation which conforms to the general syllabification rules (in this case ...V: - C...). It has a reduced stress on the second element of the compound. This syllabification will be used in relaxed speech when the compound has a high degree of expectancy and the speaker does not insist on the meaning of the individual morphemes.

In sentences (4) and (5) the test words were given contrastive stress. In the context used here the speakers used a stress pattern which adds prominence chiefly to the second element of the compound.

The test word manär is composed of segments that minimize the effect of articulation on laryngeal muscles and is expected to reveal the effect of prosodic gestures (tone, stress). In the test word tågångare on the other hand, the t- and g-gestures are expected to influence laryngeal activity.

All of the test words were put in the frame dɛ.va - han sɑ (it was - he said) and each test sentence was uttered 15 times in a series with a short pause after each item.

Subjects

The subjects were L (male) speaking Standard Central Swedish and E (female) speaking a Skåne dialect. The different pitch contours by which the grave accent is manifested are typical of the dialects. (Compare Figures 5, 6, 7, 8.) Figures 1 and 2 show some spectrographic examples of the test words.

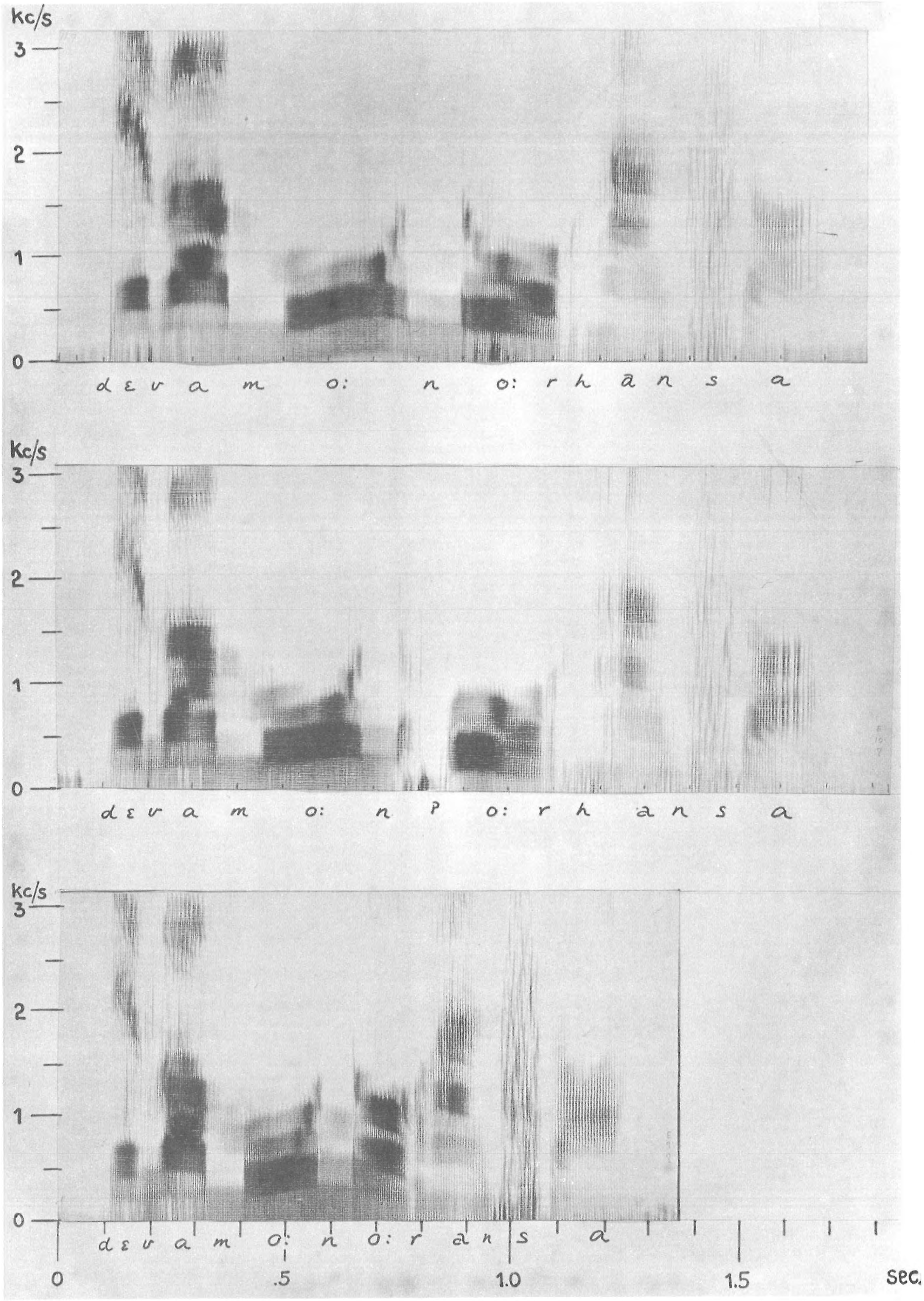


Figure 1. Spectrographic examples of the sequence <u>månår</u> pronounced with different boundaries. From top to bottom, [ˇmo:ˋno:r], [ˇmo:nˋo:r], [ˇmo:no:r]. Frame, dɛ vɑ - han sɑ. Speaker E.

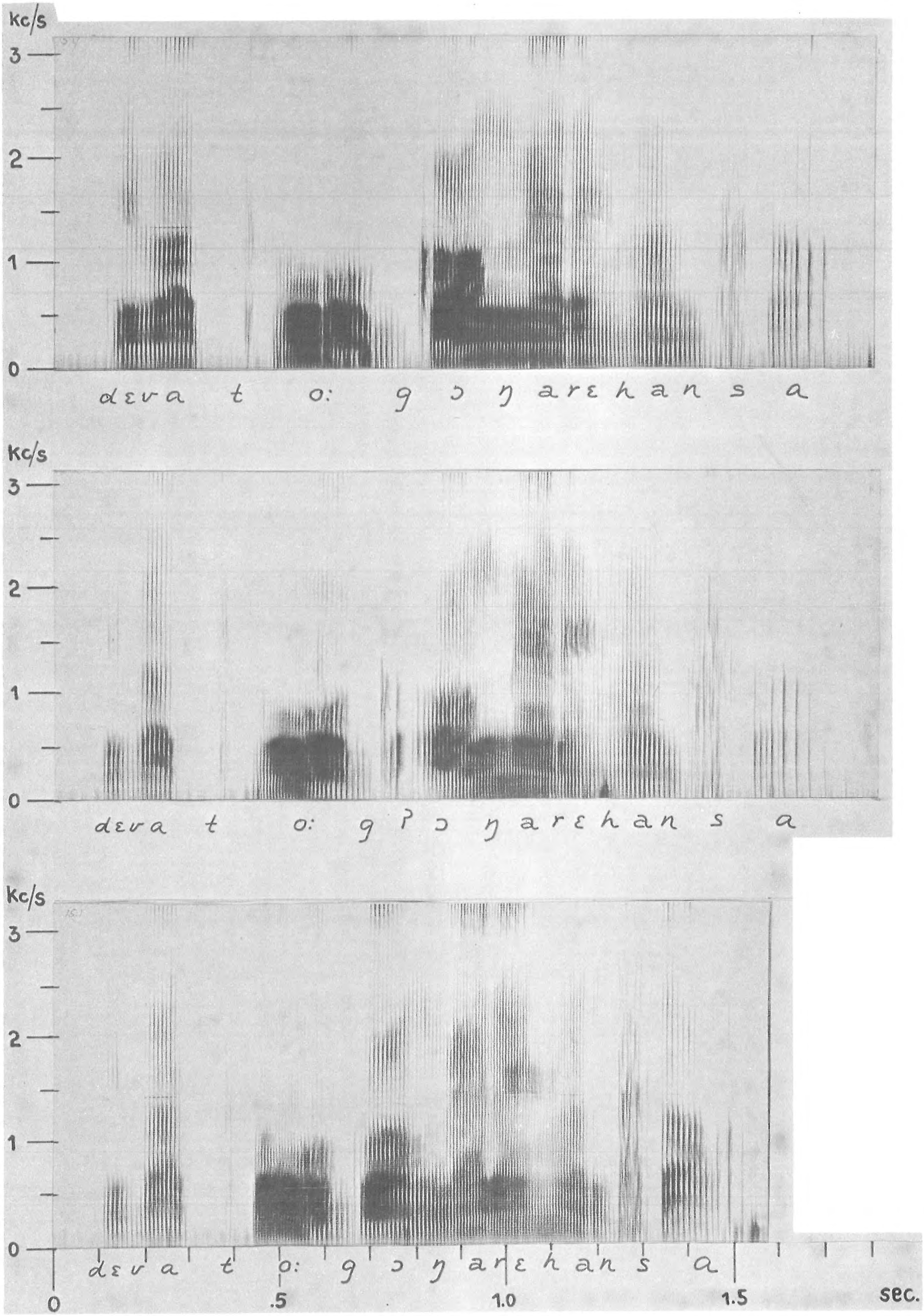


Figure 2. Spectrographic examples of the sequence tågångare pronounced with different boundaries. From top to bottom, [˘to:`gɔŋarɛ], [˘to:gɔ̀ŋarɛ], [˘to:gɔŋarɛ]. Frame dɛ va – han sa. Speaker L.

EXPERIMENTAL PROCEDURES

The EMG data were obtained by means of double-ended hooked wire electrodes which were inserted through the skin and other tissues of the neck. (For a full description of the technique see Hirose et al., 1970.) Figure 3 shows the pertinent muscles.

The amplified EMG signals and the speech signal which had been recorded simultaneously on magnetic tape were fed to a PDP-9 computer through an AD converter for data processing. In this process the EMG signals were sampled every 250 microseconds and the values were converted into 6-bit levels. The digitized values of these samples were then averaged over a running window with a range of 10 msec. Out of 15 utterances of each test sentence, 10 were selected by auditory analysis and processed in this way. The resulting records of each set of 10 were then lined up in time with respect to some easily identified speech event and superimposed giving the final record as shown in the figures. Different choices of line-up points proved to give very slight variations in the pictures. Figure 4 shows examples of our averaged and processed data.

EXPECTED EMG CORRELATES

From what we know of internal juncture in Swedish and the activities of the muscles under investigation we should expect the following EMG correlates:

1. Glottal stop

Vocalis m. There should be vocalis activity during the glottal stop in VC + V sequences. The vocalis muscle has been shown to be active for glottal stops (Faaborg-Andersen 1957, Ohala 1970, Hirose et al. 1970, Gårding et al.

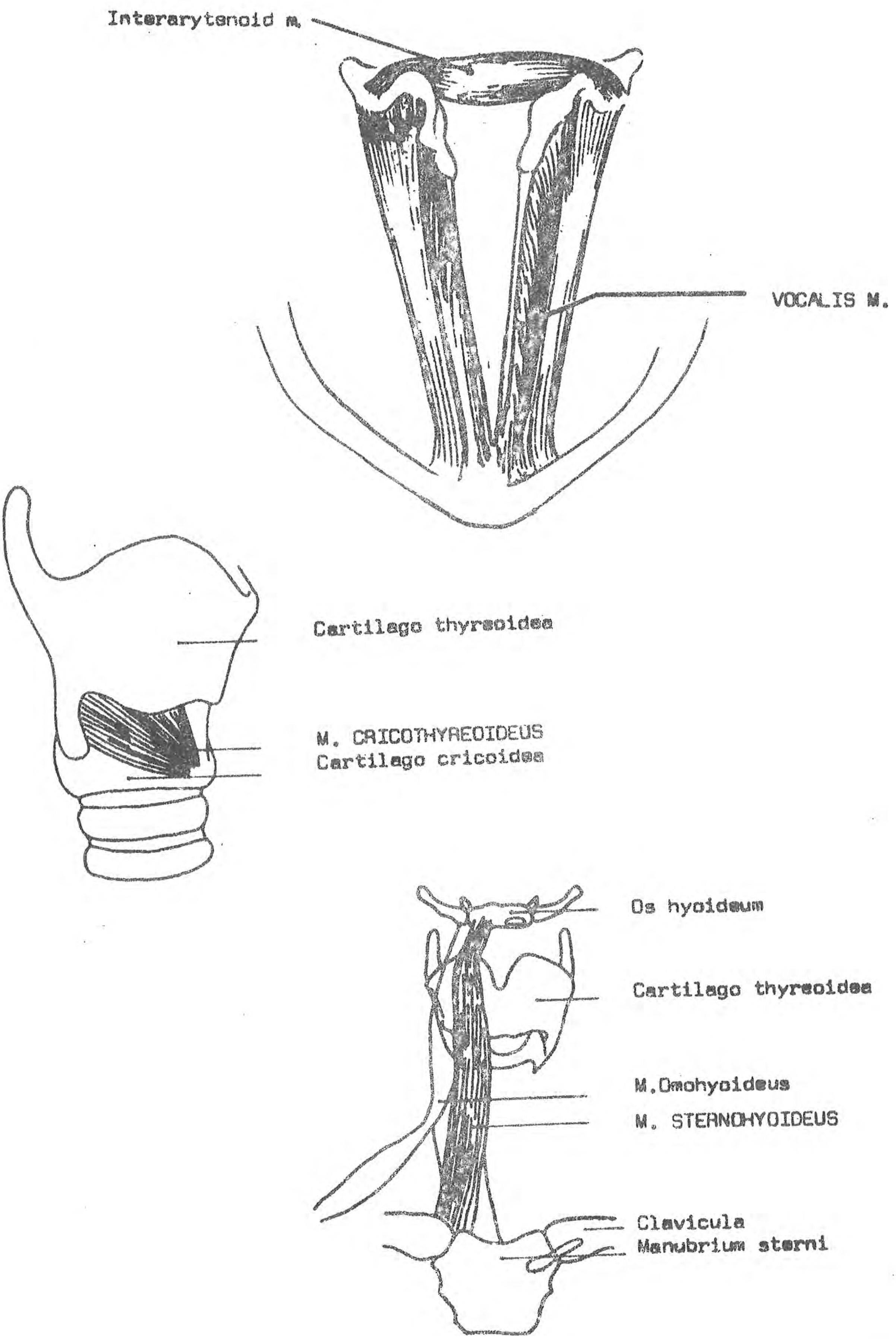


Figure 3. The target muscles. (From Ohala 1970, Hirano and Ohala 1969, and Kamijo 1966.)

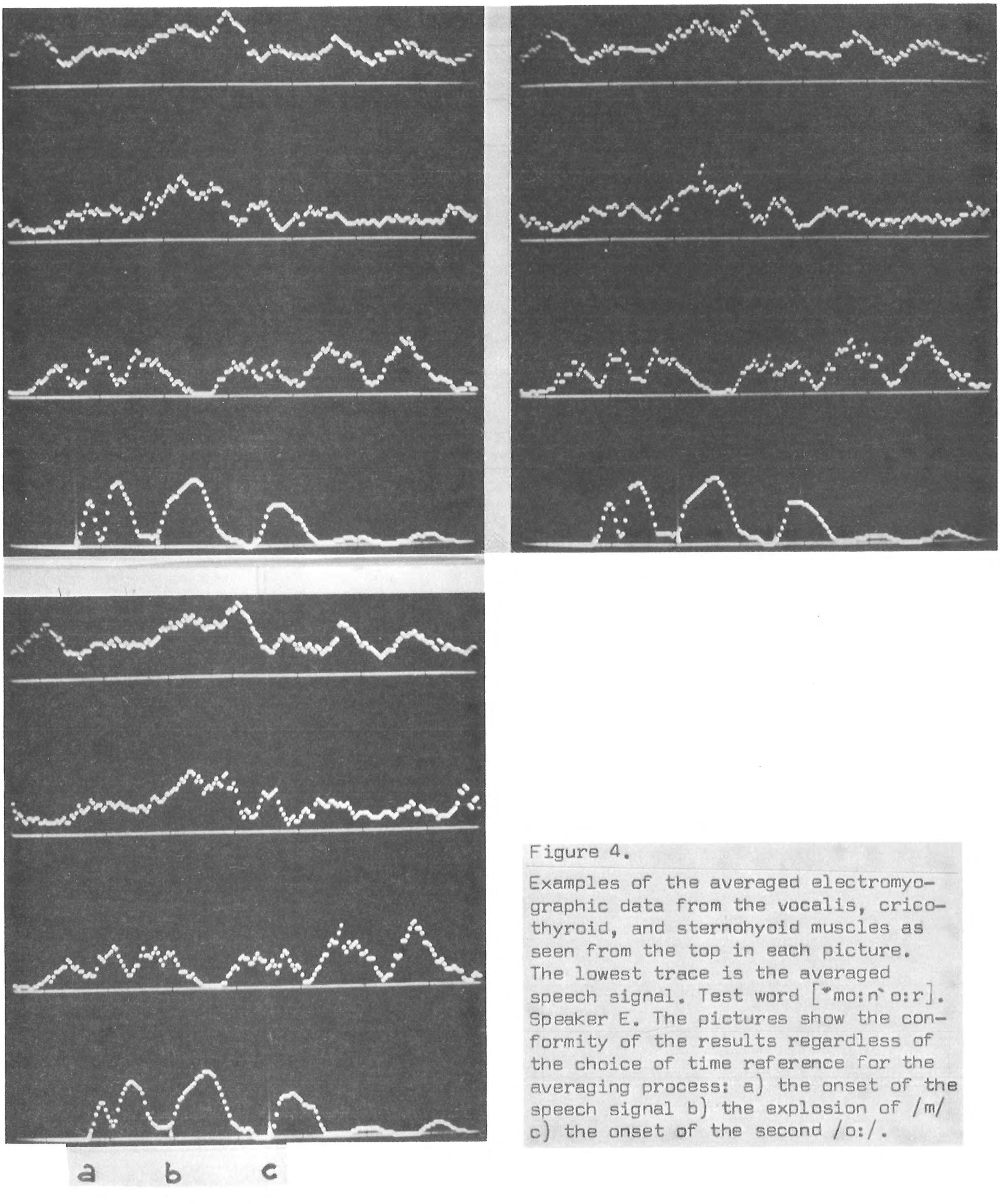


Figure 4.

Examples of the averaged electromyographic data from the vocalis, cricothyroid, and sternohyoid muscles as seen from the top in each picture. The lowest trace is the averaged speech signal. Test word [˝mo:n`o:r]. Speaker E. The pictures show the conformity of the results regardless of the choice of time reference for the averaging process: a) the onset of the speech signal b) the explosion of /m/ c) the onset of the second /o:/.

1970). Figure 5 shows for comparison conscious glottal stop gestures described in our earlier report. Notice that the cricothyroid activity seems to be suppressed at the time when the vocalis muscle has a peak of activity in connection with the glottal stops.

2. *Timing*

Sternohyoid m. According to spectrographic data (Gårding 1967) intervocalic C comes earlier in a VC + V sequence as compared to a V + CV sequence. When C = g, as in *tågångare* the C gesture is associated with tongue retraction which is known to involve the sternohyoid muscle (Ohala and Hirose 1970). Hence an earlier burst of activity is expected in *tåg+ångare* as compared to *tå+gångare*.

Cricothyroid m. In the previously mentioned EMG investigations of laryngeal muscles, the cricothyroid muscle appeared to correlate positively with the major movements of the pitch curve. Since the pitch curve is also influenced by variations in oral pressure caused by the articulation we can expect the cricothyroid record to represent a "cleaner" prosodic signal.

3. *Stress*

Reduced vocalis-cricothyroid activity is expected when stress is reduced as in the shift from a marked morpheme boundary to a syllable boundary. The vocalis and cricothyroid muscles have been shown to cooperate for pitch rising in stressed syllables. (See the works, cited above, and Sawashima et al. 1969.)

Contrastive stress is expected to enhance the difference in laryngeal activity associated with a shift of boundary. Contrastive stress was found to increase the EMG signal amplitude associated with consonant phonemes by 10-20 percent (Harris et al. 1968). A change of lexical stress had no such effect.

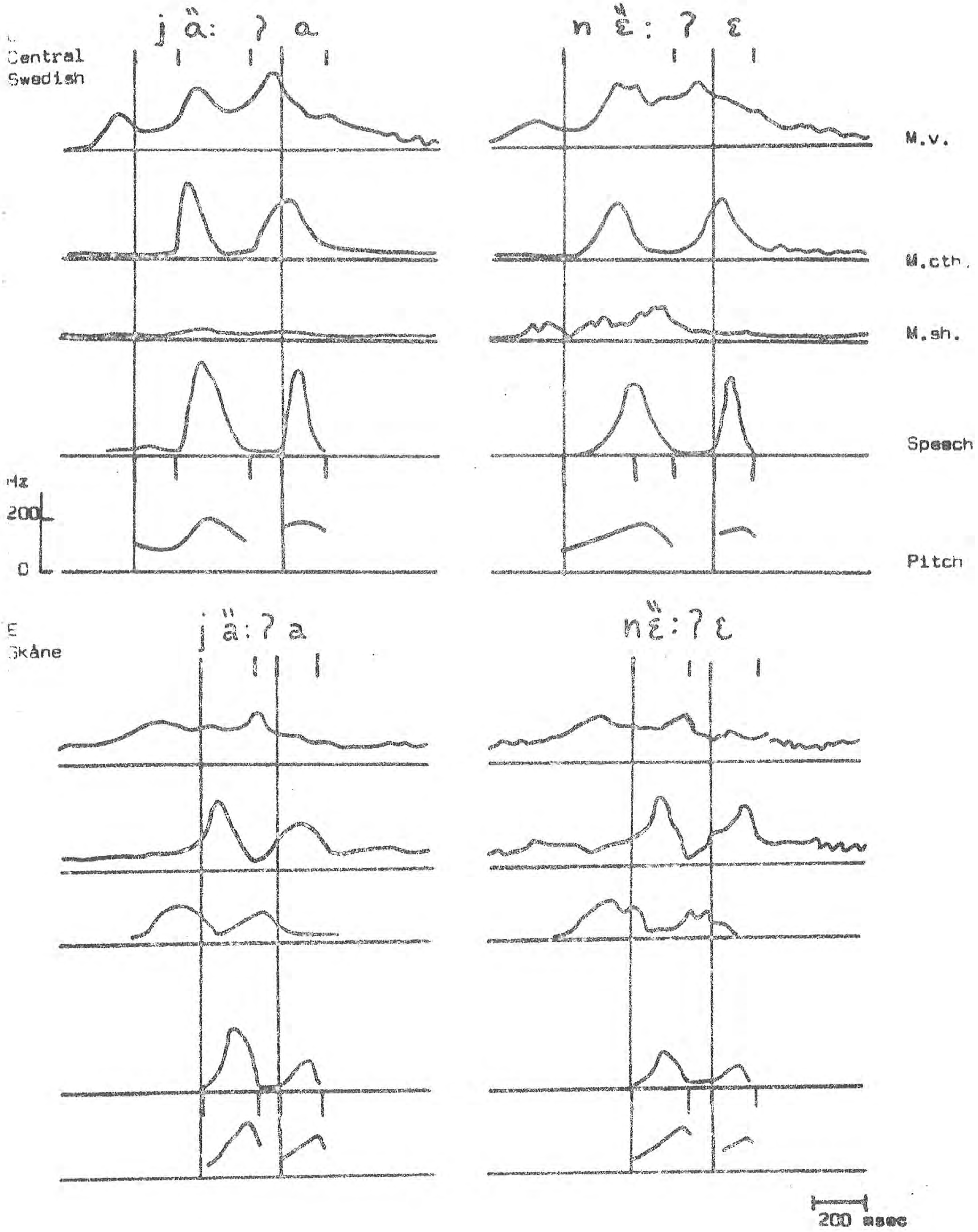


Figure 5. Data from expressive utterances with deliberately produced glottal stops. Speaker L above and E below. From Gårding et al. 1970

RESULTS AND DISCUSSION

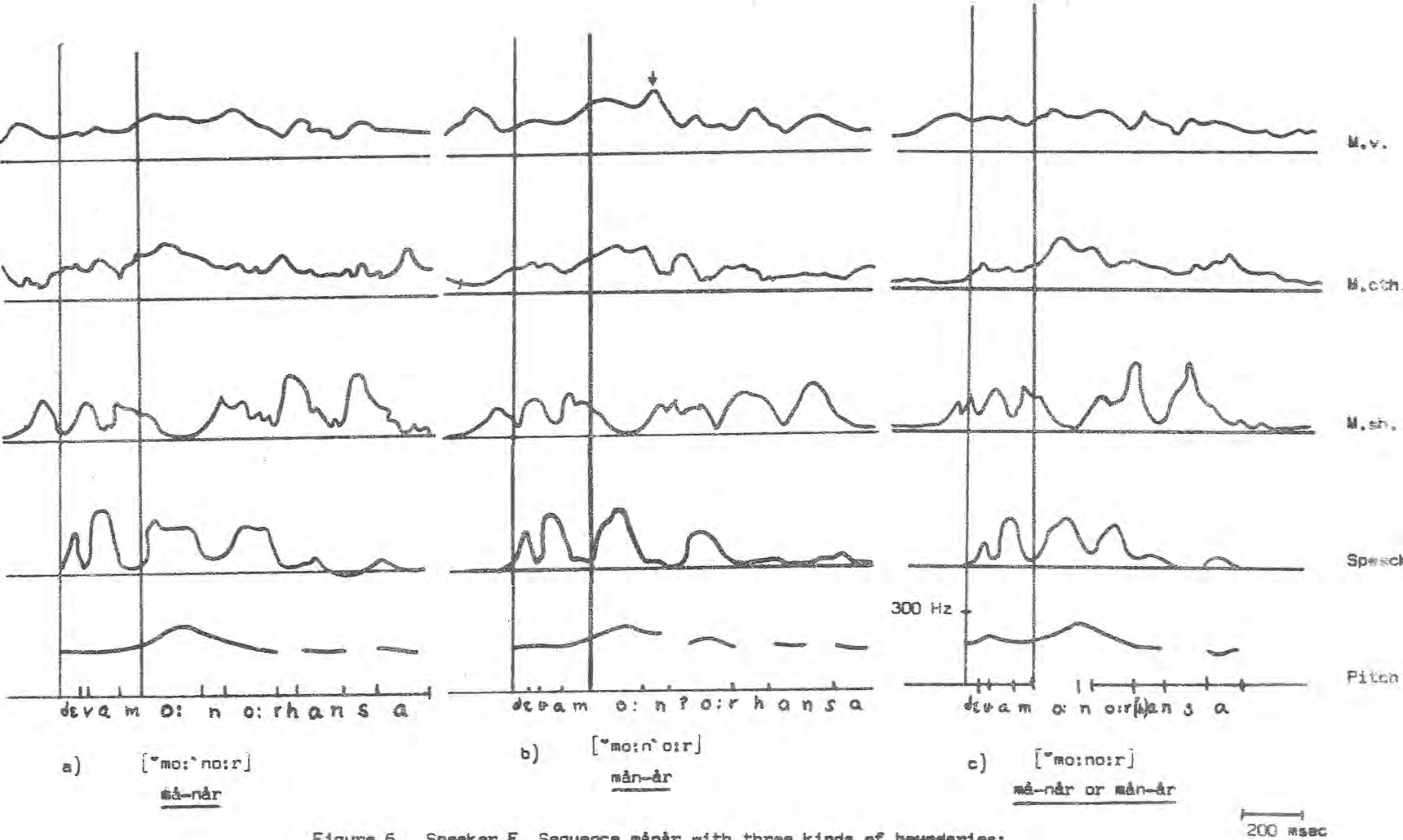
Figures 6–8 show some results of the experiment. Each of the EMG-curves represents an average of 10 utterances. They have been derived from the vocalis, the cricothyroid and the sternohyoid muscles. The fundamental frequency curve shown as the lowest trace in the figure is the hand-made average of three representative utterances.

Figures 6–7 are derived from Speaker E, Figure 8 from Speaker L. The first vertical line represents the beginning of the speech signal, the second line connects the reference points used for the summation process, i.e., for the test word *månår* the release of [m], and for *tågängare* the release of [t].

In the following we shall comment mainly on observations concerning boundary problems. For EMG correlates to other speech gestures in the material see Gårding et al. 1970, Gårding 1970, and forthcoming.

Effects of a morpheme boundary shift

Glottal stop. With a shift of boundary from ...V + CV... to ...VC + V... we notice: A gap in the broad band spectrogram before the postjunctural, initial vowel which is preceded by a schwa segment with relatively slow vocal cord vibration (Figure 1 a and b). The comparable spectrogram in Figure 2 b [ˇto:gˋɔngarɛ], derived from a test sentence with the same placement of juncture uttered by Speaker L, has an absolute gap of much shorter duration. However, this gap is followed by a segment caused by the creaky onset of the following vowel which because of its scant supply of spectral energy is similar to a gap. The duration of these two successive gaps in Speaker L's utterance is comparable to that of the single gap in Speaker E's. The perceptual effect must be similar in this respect: the segments

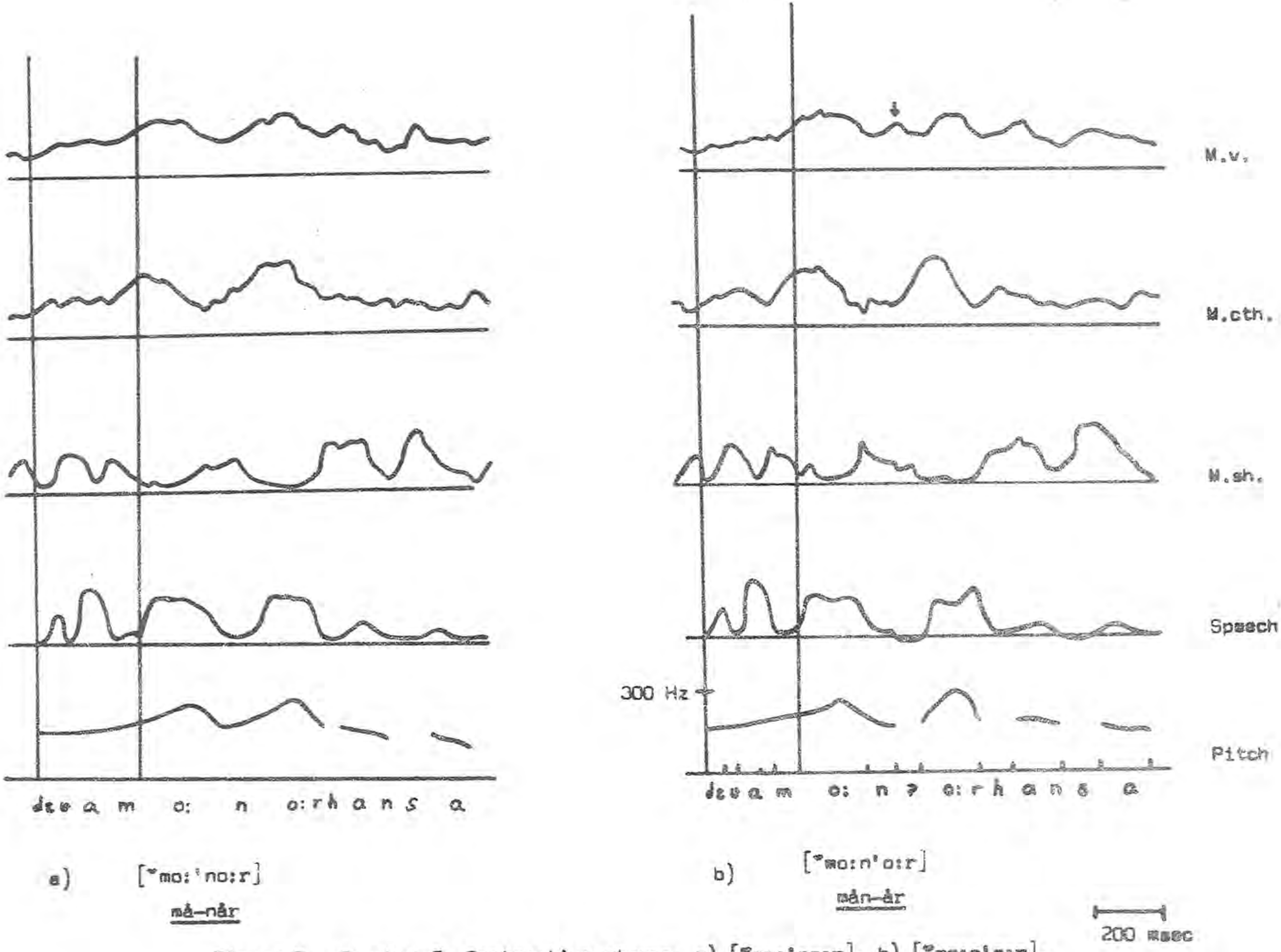


a) [ˇmo:ˋno:r]
må-når

b) [ˇmo:nˋo:r]
mån-år

c) [ˇmo:no:r]
må-når or mån-år

Figure 6. Speaker E. Sequence månår with three kinds of boundaries: a) [ˇmo:ˋno:r], b) [ˇmo:nˋo:r], c) [ˇmo:no:r]. The pitch curve is the average of three representative utterances.



a) [ˇmo:'no:r]
må-når

b) [ˇmo:n'o:r]
mån-år

Figure 7. Speaker E. Contrastive stress. a) [ˇmo:'no:r], b) [ˇmo:n'o:r].

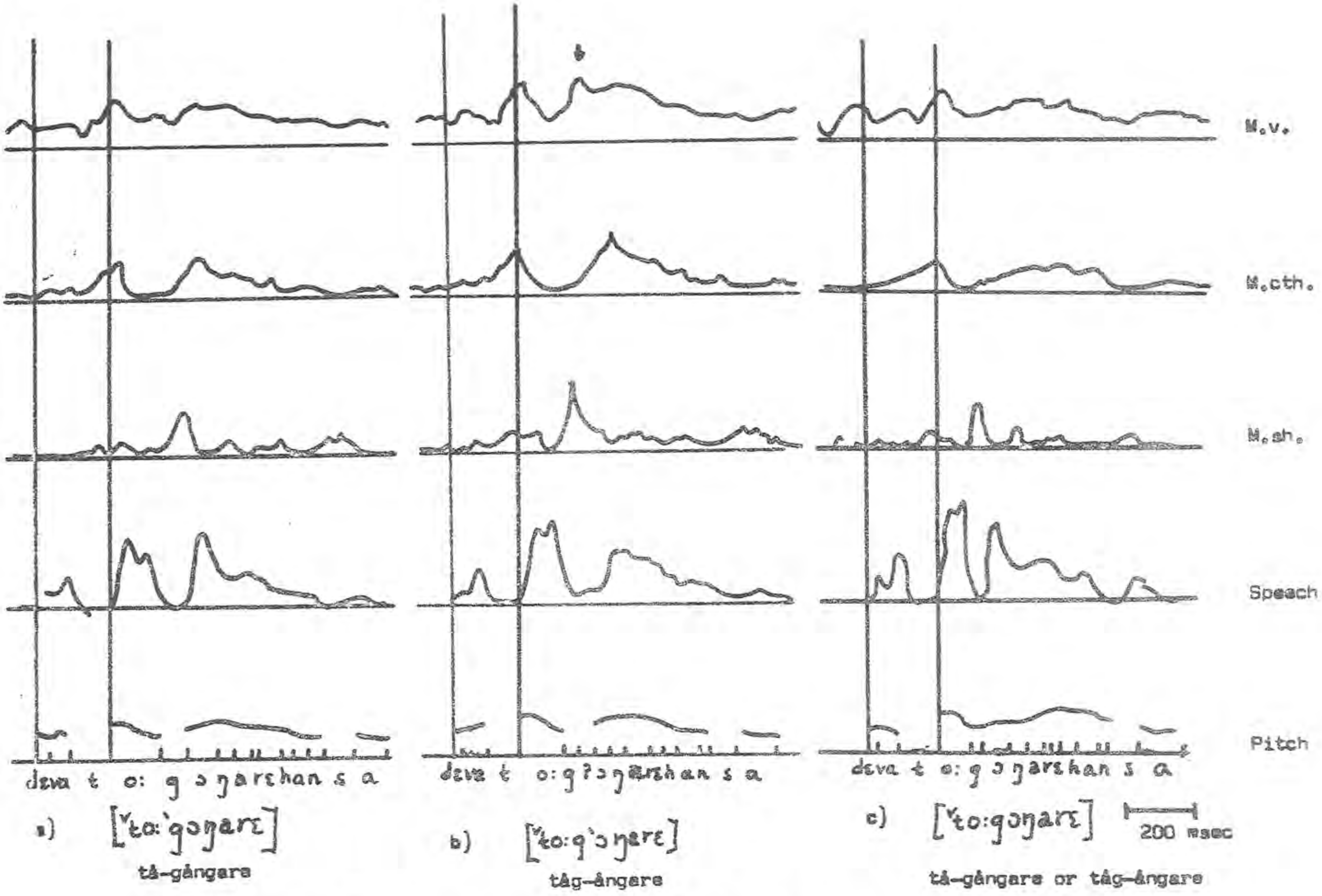


Figure 8. Speaker L. Sequence <u>tågångare</u> with three kinds of boundaries: a) [ˇto:ˋgɔŋarɛ], b) [ˇto:gˋɔŋarɛ], c) [ˇto:gɔŋarɛ].

separate C+ from the following syllable kernel. It can be inferred from the spectrograms that Speaker E produces the boundary in a ...C + V... sequence by means of a glottal closure and a softly attacked vowel and that Speaker L makes a less complete closure which permits the vocal cords to vibrate slowly. For both speakers the vocalis muscle has an EMG peak which correlates to the acoustic gap and during this time the cricothyroid muscle is more or less passive. (An arrow points to these vocalis peaks in Figures 6, 7, and 8.)

This vocalis-cricothyroid interrelation is consistent in all the ...VC + V... sequences of our material. There is also a constant timing difference between the two speakers. For Speaker L (Figure 8 and also Figure 5) the vocalis peak associated with the glottal stop appears toward the end of the gap, for E it appears prior to the closure. It seems possible to associate E's earlier vocalis peak with the sudden and total glottal closure whereas L's peak may be connected with the creaky vowel onset.

The vocalis peaks observed in connection with the glottal stops may be interpreted as active laryngeal boundary gestures typical of the ...VC + V... sequence. Notice for cmparison the acoustically similar creaky utterance endings in <u>sa</u> (Figures 1 and 2) which are not connected with any vocalis activity.

We have seen that the cricothyroid and vocalis muscles, which have been found to cooperate for major pitch rises, have a different reaction pattern for glottal stops. Figure 9 (from B. Sonesson, <u>Human vocal folds</u>, to be published) illustrates the mechanical effects of contraction in these two muscles.* When the vocalis muscle contracts, the arytenoids will be pulled forward and the vocal folds will be shortened. This shortening effect can

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* I am grateful to Doctor B. Sonesson for many explanations and discussions and for lending me the drawing appearing as Figure 10.

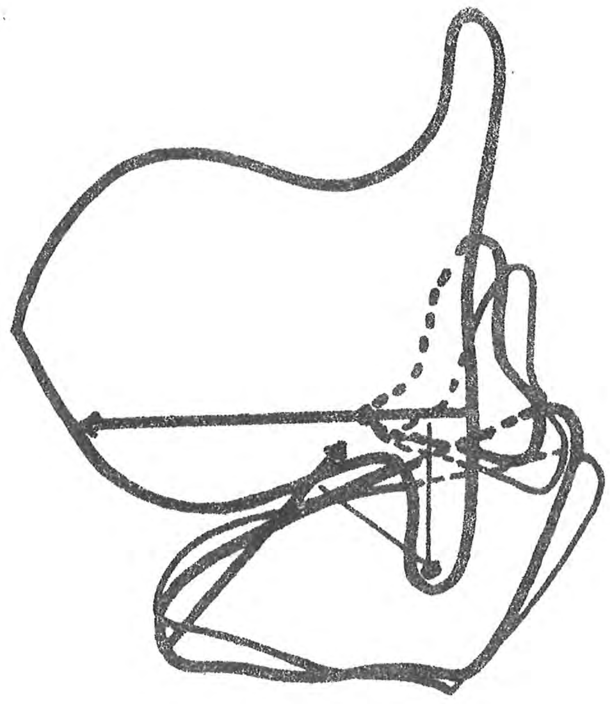

Figure 9. Mechanical aspects of vocalis and cricothyroid activity. The horizontal arrow shows the direction of the vocalis force. The slanted arrow indicates the force of the cricothyroid muscle. The straight lines drawn perpendicular to the arrows represent the levers from the cricothyroid joint. From Sonesson, Human vocal folds, to be published.

develop only if there is no counteracting force due to activity in a muscle working in the opposite direction as for instance the cricothyroid muscle. It has been found by visual inspection that the vocal folds are shortened and bulged for glottal stops. Hence it is natural that the cricothyroid muscle **should** not be activated for glottal stops. When the vocalis and cricothyroid muscles contract simultaneously the cricothyroid force prevents the vocalis muscle from being shortened. The vocalis activity will then produce the inner tension in the vocal fold needed to raise pitch.

Timing. With /g/ as the intervocalic consonant as in Figure 8, we can see the different timing of the intervocalic consonant gesture in the sternohyoid record. A comparison of [ˇto:gɔnarɛ] and [ˇto:gˋɔ narɛ] shows that the major sternohyoid peak, which is probably connected with the g-release, comes earlier when /g/ is syllable final both absolutely and in relation to the intensity maximum of the preceding vowel. In the given context it also has a faster buildup of activity. These findings are in agreement with the observations of the formant movements of the intervocalic consonant in the earlier study (Gårding 1967).

The cricothyroid activity connected with the pitch rise in the second syllable of the test sequence månår (Figures 6 and 7) is differently timed depending on the boundary location. When the intervocalic consonant is syllable initial, for instance in [ˇmo:'no:r], Figure 7 a, the cricothyroid curve starts rising prior to the /n/ segment. In [ˇmo:n'o:r] on the other hand the corresponding cricoothyroid rise comes after /n/ obviously in connection with the initial vowel. These data suggest that the activation of the cricothyroid muscle for the pitch rise is tied to the beginning of the syllable independently of the syllable's articulatory characteristics.

The time interval during which the cricothyroid muscle is activated for the pitch movement of the first syllable is comparable in the two test words må-når and mån-år (Figure 7). This suggests that the duration of the prosodic signal is dependent on the degree of stress rather than the number of phonemes of the syllable. For the second syllable, however, the cricothyroid activation time is longer in når than in år. The cricothyroid activity starts rising prior to the /n/ in når whereas in år the rise starts in connection with the initial vowel . Earlier considerations of the vocalis-cricothyroid interaction make it natural to assume that in this case the glottal stop gesture interferes with the prosodic gesture and delays the pitch rise.

Stress. Figure 10 compares the test word må-når under normal (?) and contrastive stress. The two sets of curves have been superimposed with the beginning of the speech signal as their common reference line. It is obvious that the difference in muscular activity is mainly localized to the second syllable of the test word. The pitch curve derived from the contrastively stressed utterances has a prominent peak in this syllable which is obviously related to increased vocalis-cricothyroid activity. In spite of the fact that listeners still regard the first syllable as carrying the main stress (as shown in a test), there is no evidence that the EMG signal amplitudes for this syllable are influenced by the contrastive stress. We notice a difference in the duration of certain acoustic segments however. The consonantal occlusion is longer in the emphasized word both in the initial and intervocalic nasals. This suggests a different time program for the gestures in the two test words which is also evidenced by the sternohyoid record.

According to Fromkin (1966) a syllable initial /b/ has a stronger EMG signal (orbicularis oris) than a syllable final /b/. But Harris et al.

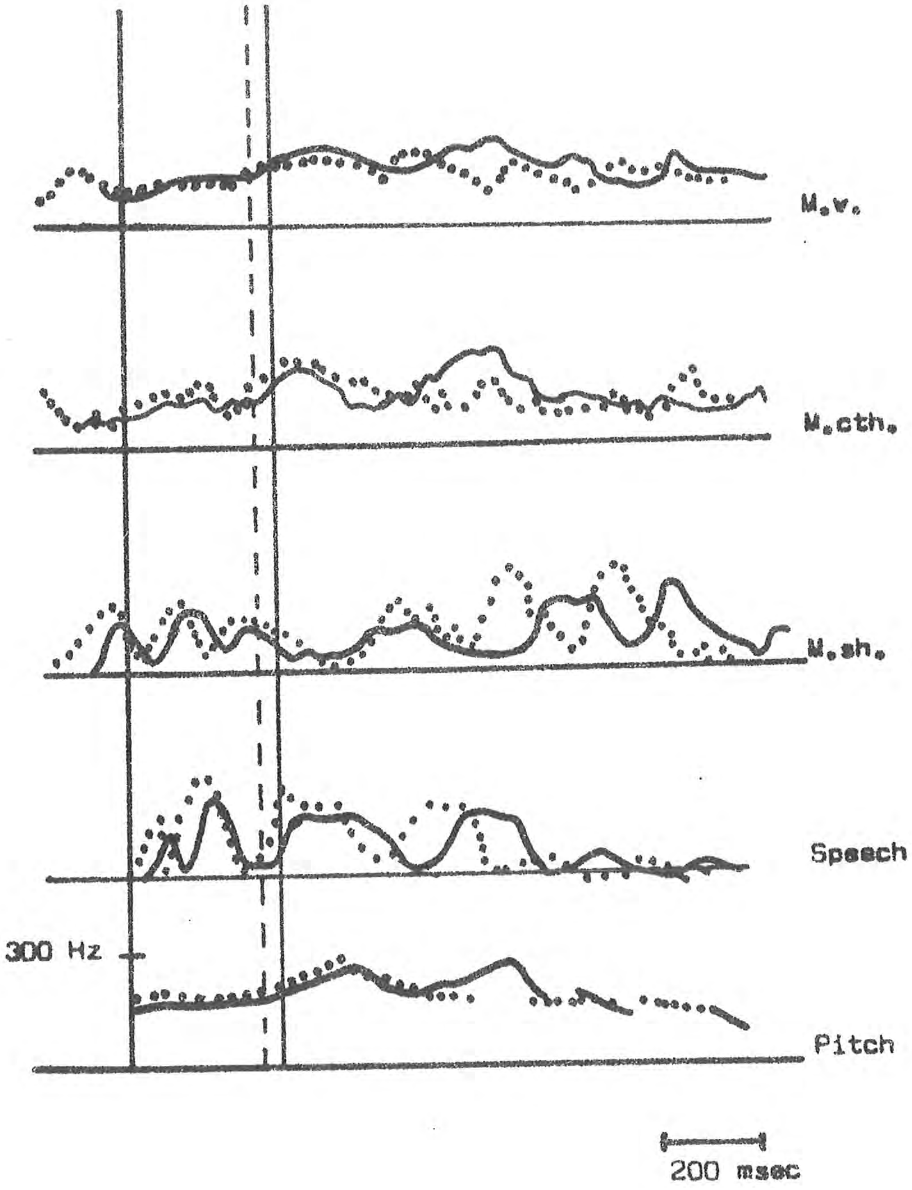

Figure 10. Speaker E. Sequence må-når with the same boundary location under normal (broken line) and contrastive (unbroken line) stress. The curves are superimposed with the onset of the stress. The curves are superimposed with the onset of the speech signals as their common time reference. The following vertical lines are the time references for the averaging process.

(1965), found no significant difference in this respect. The present sternohyoid data suggest that the syllable final /g/ in 8 b requires a higher degree of muscle activity than the syllable initial /g/ in 8 a and c, an interpretation that has support in the spectrograms (Figure 2) which show a greater amount of acoustic energy in /g+/ as compared to /+g/. All these different results may perhaps be explained by the great stylistic variability of syllable final consonants. In this position a consonant may vary from weak to strong, and the strongest variant is often released with a following voiced or voiceless schwa element, which actually makes the final consonant comparable to a syllable initial one. In the context used here the speaker probably made a conscious effort to keep the consonant separated from the following syllable, hence the stronger burst of activity noted in the EMG signal.

To sum up our observations in Figures 6-8, the location of a morpheme boundary is traceable to the laryngeal muscles that have been the targets of this investigation. In a sequence ...VC + V... the boundary is controlled by the vocalis which contracts for the glottal stop after C+ and brings about a larger separation of the two syllable kernels. There is also some evidence in our EMG data that the activity of the cricothyroid muscle which regulates the observed pitch patterns is closely timed with the syllable.

Morpheme boundary and syllable boundary

Figures 8 a and 8 c illustrate the difference between a sequence pronounced with an unambiguous realization of a morpheme boundary [ˇto:ˋgɔnarɛ] and the same sequence pronounced at a higher rate of utterance with an ordinary syllable boundary [ˇto:gɔnarɛ]. The location of the boundary with reference to the segments involved is the same in the two sequences.

Stress. The test word [ˇto:ˋgɔnarɛ] has a higher degree of subjective stress in the second syllable than [ˇto:gɔnarɛ]. This higher stress does not produce a larger energy output but the pitch curves are different. In the first case the pitch starts falling earlier and the vocalis and cricothyroid muscles have higher and earlier peaks. In addition, the spectrograms show a longer occlusion and a longer open interval with stronger energy for the more stressed /g/.

Timing. Because of the longer duration of the segments pertaining to /g/ in [ˇto:ˋgɔnarɛ], the syllable kernels of the first two syllables are wider apart. The acoustic gap relates to a very small peak in the vocalis muscle and a passive phase in the cricothyroid. The combined behaviour of the two muscles actually looks lika a glottal stop gesture. – After the longer occlusion in [ˇto:ˋgɔnarɛ] there is of course a delay in the timing of the gestures for the rest of the utterance.

The two compared test words [ˇto:ˋgɔnarɛ] and [ˇto:gɔnarɛ] have as was already mentioned the same syllabic division. We notice that the major sternohyoid peak is similarly timed realtive to the intensity peak of the following vowel and has the same signal amplitude regardless of the difference in stress pattern. This relation shows that the sternohyoid peak is connected with the g-release. The timing of the peak in relation to the preceding vowel is different however. In [ˇto:gɔnarɛ] the peak has a fast rise, whereas in [ˇto:ˋgɔnarɛ] the rise is slow which may be indicative of a slower articulatory movement. The most conspicuous spectrographic difference in the two test words is a longer occlusion for /g/ in [ˇto:ˋgɔnarɛ].

The preceding observations may be summed up in the following way. With a shift of boundary from ...VC + V... to ...V + CV... to ...V – CV... the two syllables come closer. This process occurs at the expense of stress in the second syllable and at the expense of the duration of a glottal or oral closure or constriction. The glottal closure is most pronounced in the ...VC + V... sequence.

One other aspect of the same process can be expressed as follows. Two stressed syllables in succession seem to require a relatively long closure or constriction interval after the first syllable. During this interval the subglottal pressure needed for the second major stress is probably being restored.

Concluding remarks

On the basis of the spectrographic study (Gårding op.cit. p. 133 ff.) it was assumed that in sequences ...V_1 + CV_2... the articulatory program must be simpler than in sequences ...V_1C + V_2... Using Öhman's coarticulation model (Öhman 1967) the consonant in ...V + CV... could be regarded as superimposed on vocal tract shapes that gradually change from V_1 to V_2. In V_1C + V_2 on the other hand, C has resonances that indicate an intervening change in the vocal tract configuration from V_1 to schwa to V_2. In other words, C+ seemed to coarticulate mainly with schwa and +C with V_2. The glottal closure or constriction in connection with the initial postjunctural vowel in ...VC + V... also suggested a more complex innervation pattern.

The EMG data obtained from the vocalis and cricothyroid muscles in the present study are in agreement with the view that a ...VC + V... sequence requires a more complicated set of signals to the vocal apparatus than a ...V + CV... sequence. The glottal closure gesture in ...VC + V... calls for a differentiation in the activities of the two muscles which in the EMG records of the ...V + CV... sequences show a smooth cooperation.

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