Prediction of velum movement from phonological specifications

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Centre National d'Études des Télécommunications, Lannion, France
(submitted to Phonetica)

Abstract

The vertical movement of a sample point of the velum surface in sentences uttered by two speakers of English has been investigated. The temporal patterns of velum movement were approximated with a series of rules. Our findings suggest

(1) that the feature [+ nasal] alone fails to explain velum height movement patterns,

(2) that there are no target values for the velum for the vowels (at least in the material under investigation),

(3) that the prosodic or configurational factors such as intra-syllabic position and stress patterns strongly influence velum height, the speed of velum movement, and the timing of velum gestures, and

(4) that the strategies used by the two speakers are different with respect to control of movement velocity.

We propose a suprasegmental feature [+ strong] to account for observed movement patterns including timing relations between velum raising and lowering gestures and articulatory gestures of consonantal articulators such as the lips and the tongue tip.

Material and Method

This paper presents preliminary results of an investigation of velum movement in sentences. The articulatory data were obtained with the computer-controlled X-ray microbeam system at the University of Tokyo (Fujimura et a1., 1973 ; Kiritani et al., 1975). They were analyzed using the facilities developed at AT & T Belt Laboratories (Miller and Fujimura, 1982; Miller, 1973). A total of 52 sentences and a large number of isolated words pronounced by five native speakers of American English were available for this study. In this paper we report on the results of analyzing 22 sentence utterances produced by two speakers, whose velum movements suggest strikingly different strategies. The list of the available sentences for the two speakers is given in Table 1.

Insert Table 1 here

The velum is a relatively difficult organ to study with the microbeam system, because it is difficult to attach a metal pellet on its surface by nontoxic glue directly, primarily due to constant secretion and relative inaccessibility. For this reason, a pellet (a 3-mm coated lead sphere) was glued on the far end of a flexible plastic strip, which was inserted through the nostril of the subject and was fixed outside the nostril, in such a way that the pellet rested on the upper surface of the moving part of the soft palate in the upper pharynx. The location of the pellet was estimated to be near the midpoint between the posterior edge of the hard palate and the tip of the uvula, but the exact location is not known. This pellet positioning technique was developed by Dr. H. Hirose at the University of Tokyo. The data acquisition was conducted by Drs. O. Fujimura, S. Kiritani, H. Hirose and their associates.

Insert Figure 1 here

Figure 1 illustrates the movement trajectory, as observed laterally, of the velum pellet as well as of other pellets for one of the sentences. We will consider the vertical position of the velum pellet as the measure of velum height. All pellet positions were evaluated relative to the maxilla, correcting for head movements during utterances using two reference pellets fixed to the upper tooth and the bridge of the nose. Pellets were placed in the mid-sagittal plane.

Insert Figure 2 here

Figure 2 represents the velum height time function in the same sentence and two other sentences uttered by the same speaker (i.e., speaker A). The speech signal envelope is shown below each velum time function. The speech signal could be played and listened to for any selected time intervals by an interactive analysis program, in order to verify the phonetic quality of the part or the material in question. Our goal is to determine the control variables that explain the behavior of the velum in such sentences. In particular, we attempt to predict velum height, velum movement velocity, and timing of velum movements relative to the speech waveform and to movements of other articulators.

In order to approach a solution to this complex problem, we followed a procedure of successive approximation, starting from careful but subjective interpretation of data, followed by hypothesizing a set of quantitative rules for predicting the time function of velum position for a given phonological representation of each utterance, then followed by revisions of the rule system and repeating the cycle. The rules were not implemented as computer programs, but were manually implemented to generate time functions (strictly according to the hypothesized rule system). Automatic interpretation of large varieties of utterance materials awaits future studies for testing the validity and completeness of our present tentative model.

Velum pellet height data were originally sampled at 8.5-ms intervals. They were subjected to minimal digital smoothing and plotted as time functions using the same position (ordinate) and time (abscissa) scales for all data studied, maintaining the same origin of the ordinate for the same speaker for comparison of different utterance samples. Time function curves from the same speaker (and the same session) were superimposed and manually copied on semi-transparent paper, with the time origin for each sample being adjusted appropriately for the purpose of comparison wherever applicable. Tracings of different data channels, such as velum height and acoustic signals, were obtained by maintaining the common time scale and origin. All figures illustrated in this paper were obtained in this manner, even though the magnification varies from figure to figure. Wherever appropriate, data from other subjects were consulted in interpreting results, but quantitative analyses pertain to the two speakers only.

Segmental and suprasegmental factors affecting velum height

Nasality Feature

First, we should note that velum lowering as the phonetic manifestation of a nasal consonant does not necessarily result in a velum height valley in the time course of velum movement, as expected from a segment concatenation and smoothing point of view.

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Insert Figure 3 here

Often, for example, the velum height minimum is found in the preceding acoustic vowel segment (i.e., before the articulatory closure for the nasal murmur) in a syllable containing a final nasal consonant. As expected, the velum was found in general to have a high position for consonants that are phonologically classified as oral ([- nasal]), and a low position for those consonants classified as nasal ([+ nasal]). Figure 3 illustrates the superimposed velum height time functions in utterances containing ([- nasal] consonants (fig. 3a), and in utterances containing [+ nasal] consonants (fig. 3b) for speaker B. As seen in figure 3, the stationary value of velum height for the [- nasal] consonants (fig. 3a) generally represents a peak of velum movement and is higher than that for the [+ nasal] consonants (fig. 3b). For a nasal consonant in the environment of [- nasal] segments (excluding vowels, see below), the velum time function has a local valley, which falls within the time interval of the acoustic nasal murmur. However, the [+ nasal] feature for a consonant is not sufficient to determine velum height; as can be seen from figure 3, both the maximum velum height achieved for [- nasal) consonants and the minimum velum height achieved for [+ nasal] consonants vary a great dear depending on the context.

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Insert Figure 4 here

Nasality of Following Segmental Context

It has been discussed in the literature that the velum exhibits anticipatory lowering when the following context contains a nasal consonant (Henke, 1966; Moll et al., 1971 ; Kent et al., 1974, 1977). Figure 4 illustrates with speaker B the influence of the following segmental context on a [- nasal] consonant, for consonant-vowel-consonant sequences CVC and CVN (in this paper we denote a nasal consonant by N and a non- nasal consonant by C). In figures 4a and b, the first [- nasal] consonant is followed by a vowel, and then by a [- nasal] consonant (a), or by a [+ nasal] consonant (b). In both Figures 4a and b, the first consonant C is not directly preceded by a nasal consonant.

There are three differences in velum movement pattern between CVC and CVN. First, in CVC sequences, the maximum velum height for the first C is usually higher than for the first C in the CVN sequences. Second, the maximum velum height for the first C in CVC sequences varies a great deal, in comparison with CVC (compare height values at vertical lines). Third, related to the first point, the velum exhibits anticipatory lowering for the [+ nasal] consonant in some of the CVN utterances, but not in others. The anticipatory lowering, when it occurs, seems to begin during or prior to the first consonant in the CVN sequence.

By careful examination of individual time functions of velum movement, we could not find any evidence for an inherent velum position for the vowels (V). In the non- nasal context (fig. 4a), the velum is high for the vowel ; in the nasal context (fig. 4b), the velum is lower for the vowel. But, as noted before, the actual valley often occurs within the acoustic vowel segment (according to the traditional definition) when it is followed by a tautosyllabic nasal consonant. In this study, we proceeded with the assumption that English vowels, unlike consonants, are unspecified for velum height (see below for further discussion).

Configurational Environment

The time functions for CVN sequences in figure 4b were further separated into two groups and are replotted in figures 4c and d. Figure 4c represents utterances satisfying one of three configurational conditions:
(1) C immediately precedes a stressed vowel.
(2) C is in word -initial position, or
(3) C immediately precedes a major syntactic boundary.
In figure 4d, C does not occur in any of the three configurational environments. To describe this grouping of data, we devised a binary feature [± strong], to be associated with each [- nasal] consonant. The C in any of the three configurational conditions (fig. 4c) was labeled [+ strong]; otherwise C was labeled [- strong]. An oral consonant with the feature [+ strong] is less likely to be influenced by anticipatory velum lowering, in comparison to an oral consonant with the feature [- strong].

In the set of utterance analyzed here, the consonant preceding a stressed vowel are syllable-initial consonants. Since (phonologically) word-initial consonants are also syllable-initial consonants, it is tempting to associate the behavior of [+ strong] with configurationally initial consonants, and [- strong] with non-initial consonant, perhaps referring to the syllable as the configurational domain (Fujimura et al., 1976). If so, we could dispense with the feature [+ strong]. However, consonants in condition 3 (before a major boundary) are clearly not syllable-initial. It may also be noted that the consonants in category (3) were typically syllable affixes (Fujimura, 1979; Clements, in press). More data are needed to give ground to such an analysis based on syntagmatic structure.

Other Segmental Inherent Features

The feature [± strong] is not the only factor that determines anticipatory velum lowering, because the maximum velum height for the [- strong] oral consonants in figure 4d still exhibits a great deal of variation. The remaining differences in the amount of anticipatory velum lowering among the [- strong] samples and also among the [+ strong] samples where there is variation seem to be largely explainable by taking into account the inherent phonetic features of the consonant in question.
First, velum height for the non-obstruent /r/ and /1/ or clusters containing /r/ and /1/ (dotted-line time functions in both figure 4c and d) is relatively more affected by the following N, for both [+ strong] and [- strong] consonants than is the velum height for other consonants. Second, velum height for the velar consonants /k/ and /g/, as shown by the crossed-line time functions in figure 4d, is less affected by a following

N, in comparison with other consonants. In the case of the velar stops, the high velum position is probably due to direct physical interference of the tongue surface pushing up the velum. This is also why the velar nasal consonant /ŋ/ has a higher velum position than other nasal consonants (fig. 15).

Stress: Effects on Velum Position and Velum Velocity

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Insert Figure 5 here

Figure 5 illustrates velum movement in CVN utterances, contrasting stressed versus unstressed environments for both speakers. As can be seen in figure 5, for both speaker B and speaker A, the velum excursion from oral consonant C to nasal consonant N is generally more extensive in stressed syllables than in unstressed syllables. Both the peaks and valleys of the velum time functions are affected by stress; the velum height valley is not as deep for nasal consonants in unstressed syllables as it is for stressed syllable and the velum height peak is not as high for oral consonants in un tressed syllables as it is for stressed syllables.

However, the two speakers differ in terms of velum movement velocity in unstressed and stressed syllables. For speaker B the velocity of velum lowering seems to be different in stressed syllables and in un-stressed syllables; the maximum slope of the downward movement of the velum appears to be greater in the stressed syllable than in the unstressed syllables. or speaker A, in contrast, the velocity of velum lowering does not seem to depend on the stress status of the syllable ; the maximum slope of the downward movement of the velum is similar and consistent in stressed and un-stressed syllables.

Modeling Velum Height and Velum Velocity

For speaker A, the feature [± strong] was associated with a considerable difference in velum position, but did not have any direct influence on the velocity of velum lowering. The two facts may be considered consistent with Lindblom's (1963) well-known model of coarticulatory undershoot. In that model, articulatory movements between given target positions are determined by a filter, representing the characteristics of the articulator as a physical system. Undershoot of a phonologically specified target position occurs if the time interval specified for a transition from one target position to another is short relative to another is short relative to the time constant of the smoothing filter. Assuming that there is no direct control of velocity (i. e., assuming the input to the filter is always a step function) and that the target positions are the same (i. e., assuming the step size is the same), an articulator’s velocity is determined by the filter. Then we should not expect to find any difference in movement velocity until the next movement is triggered. For speaker A, in most cases, as depicted in figure 5, we may assume that the starting position for each of the stressed and unstressed conditions is nearly the same, and the descent toward the next target position follows the same time course, displaying the characteristic response function of the physical system, which may be assumed to be the same for each stress condition. The extent of descent varies reflecting only the timing of the next input step function for an ascent. The unstressed syllables are expected to exhibit shorter excursions of descending movement because the syllable duration is shorter than for stressed syllables and because the input step may be smaller. If this interpretation is correct, the coarticulatory explanation assuming a binary specification of [±nasal] can be successful in explaining velum lowering patterns for speaker A.

For speaker B the velum movement pattern as a whole crucially depends on stress condition in way not predicted by a simple smoothing filter model. In other words, for speaker B, we cannot ascribe the difference in velum movement patterns to coarticulatory undershoot. Different velocities and multiple target positions for the velum for consonant are assumed below in modeling speaker B's movement patterns, depending on the suprasegmental context, particularly the feature [± strong].

Rules for modeling speaker A

For speaker A, the velum has a target position 'low' for nasal consonants 'high’ for oral consonants. There is no target position for vowels.

Rules for Velum Lowering

The velocity of velum lowering is fixed for all stressed ‘CVNs and for all unstressed CVNs (fig. 5). The timing of velum lowering, relative to crucial articulatory events such as stop closure is determined by the manner of articulation of the consonant preceding the nasal and by the suprasegmental configuration. In order to infer the rules of relative timing, we summarized the articulatory events, depicting the relevant movement patterns for different articulators, along with the acoustic signal envelope, as shown in figure 6. An excerpt of such depicted patterns is also shown in figure 10, illustrating the timing rule for velum raising.

Figure 7 shows a flowchart for selecting the applicable rule for the beginning time of velum lowering in different case . The rules are:

L1) Begin to lower the velum at the release of the top closure (if is a stop in /CVN/).
L2) Begin to lower the velum at the middle of frication (if C is a fricative in /CVN/).
L3) Begin to lower the velum at the acoustic onset of the consonant (elsewhere in /CVN/s, and in /CN/s is [-strong].
L4) Begin to lower the velum in the middle of the vowel (in /V=N/; i.e. if the nasal occurs at the beginning of a word and the preceding word end with a vowel).
L5) Begin to lower the velum at the onset of the oral closure for the (in /C#N/, i.e., if a phrase-final C is strong and is followed by a phrase-initial N).

Figure 8 illustrates applications of these rules in three example sentences for this speaker. In this figure, the observed articulatory and acoustic events are provided as the input data, and the applications of rules (shown in circles) result in the triggering of each velum descent, as indicated by each straight downslope. The vertical dashed line relates this trigger time to the occurrence of the rule relevant articulatory/ acoustic event. The descent slope is assumed to be constant and was determined empirically to fit the observed data.

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Insert Figure 6 here

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Insert Figure 7 here

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Insert Figure 8 here

Rules for Velum Raising

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Insert Figure 9 here

Figure 9 gives a flowchart for selecting the applicable rule in different cases. There are two velocities for the velum raising movement: high and low. The velum raising movement is timed according to the segmental composition and stress status of the tautosyllabic vowel. Applications of these rules are exemplified in figure 10. The rules are:

R1) Begin to raise the velum at a constant lead time before the peak of the oral articulatory closure for the nasal consonant (i.e., the peak of the blade pellet time function for /n/, the lip pellet for the labial consonant /m/, as indicated by the down arrows in fig. 10) in /VNC/. The velum raising movement has high velocity.

R2) Begin to raise the velum *at* the closure peak for the nasal consonant in /NəC/. The velum raising movement has high velocity.

R3) Begin to raise the velum at the closure peak for the nasal consonant in /NVC/. The velum raising movement has low velocity.

Slow Component for Raising Movements (Carry-Over Effect)

We assumed two different constant slopes for velum raising, depending on context, in applying the rules stated above. However in both cases, the slope changes to a very low value (i.e., slow velocity movement). We shall call this phase of movement a slow component (or 'carry- over' effect). Apparently, the breakpoint for the onset or this very low velocity movement occurs at a fixed pellet height, *h,* as shown in figure 11.

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Insert Figure 12 here

Figure 12 displays the time course of the velum predicted by these rules. The reconstructed time functions are superimposed on the actual velum time functions for the three sentences. As can be seen for this figure, the small set of rules can describe with fair accuracy the observed time functions of velum movement for speaker A. These rules are obviously incomplete to cover all possible phonological environments of a nasal consonant in English. Also, the rules may need revisions when they are tested against more extensive data.

Rules for Modeling Speaker B

For speaker B, only one segmental feature [± nasal] and two suprasegmental features [± strong] and [± stressed] are used in the rules for reconstructing velum height, velocity and timing. In contrast to speaker A, no mention of the manner features of the oral consonant is necessary.

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Insert Figure 13 here

Figure 13 shows a flowchart for determining the velum target height and figure 14 shows a flowchart for determining velum velocity and timing. Figure 15 displays a reconstruction of the velum movement time course in sentences for speaker B.

Target Positions

For speaker B, several target positions for the velum were specified, as shown in figure 13:

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Insert Figure 14 here

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(1) 'Very high' velum position for an oral consonant if followed by an oral consonant (CVC sequence), or if it is [+ strong).
(2) 'High' velum position for an oral consonant that is [- strong].
(3) 'Low' velum position for a nasal con- sonant preceded by an oral consonant and an unstressed vowel, or (not indicated on the chart in fig. 13) after a pause. In our data, in these environments, the nasal consonant is in initial position.
(4) 'Very low' velum position for a nasal consonant in two environments: following another nasal consonant (a case of assimilation), and following a stressed vowel (the /CVN/ or /CaN/ where C is [+ strong] nasal consonant is syllable-final).
(5) No velum target position is specified for the last consonant preceding the nasal.

Velum Lowering

The rules for timing and velocity, as illustrated in figure 14, are:

LI) Begin to lower the velum at the articulatory release of the strong consonant C in /CVN/ or /C#N/ where C is [+ strong] i.e., where the [+ strong] consonant is the last consonant preceding the nasal. The velocity is high. That is, the velum starts to lower for the next nasal consonant immediately after the last [+ strong] oral consonant preceding the nasal, as soon as there are no stronger oral consonant ahead.

L2) Begin to lower the velum immediately after the release of the last [+ strong] oral consonant preceding the nasal when there are [- strong] consonants intervening between the [+ strong] consonant and the nasal ; the velocity is low. Velum height for the intermediate [- strong] consonants is affected (i. e., lowered) by such anticipatory lowering. There seems to be, however, a minimum velum height (‘high’) allowable for the [- strong] oral consonants. The velum does not lower beyond this height for [- strong] oral consonants.

The involvement of the tongue dorsum for oral or nasal palato-velar obstruents seems also to have a heightening influence on velum height (see above). For the sake of simplicity, the influences of the tongue position have not been taken into account in the reconstruction shown in figure 15.

Velum raising

R1) Begin to raise the velum in NC clusters following a stressed vowel (VNC sequences): the movement velocity is very high.

R2) Begin to raise the velum in other cases, t ol1 owing a nasal Consonant ; movement velocity is high.

There is no slow, carry-over component for velum raising for speaker B. The height of the velum in the oral consonant following a nasal consonant is not systematically lowered, as has been observed for speaker A.

Speech-Ready Gesture

No attempt was made to reconstruct velum behavior at the very beginning of sentence, because it is difficult to model by rules (fig. 12, 15). Tensing of all the muscles involved in speech production - those controlling the velum included - prior to speech is a common observation. The so- called 'speech-ready' gesture is highly variable in nature. The elevation of the velum at the beginning of the sentence does not seem to be fixed relative to either segmental events or supra segmental events. Instead, it varies apparently randomly or according to nonlinguistic factors, as confirmed by the study of velum behavior in different utterances of the same sentence by the same speaker. The striking variations in timing of the speech-ready gesture for the velum have been discussed in a previous paper (Vaissière, 1986).

Summary and Conclusion

For both speakers, the nasality target for a nasal consonant is an open velopharyngeal port and that for an oral consonant is a closed velopharyngeal port. However velum height as such is free to vary over a certain range, while the velopharyngeal port is kept closed or open correctly. (The X-ray data does not provide direct evidence that the nasal passage is actually open or closed.) But the variation follows a system of rules as discussed here; some of the characteristics may be linguistically meaningful. In this sense, the feature [±nasal] provide only a gross characterization in velum height control.

Other factors such as the suprasegmental feature [± strong], may influence the height of the velum, the velocity of velum movement, and the timing of velum gestures. This result illustrates that it is very important not to study the segmental and suprasegmental, or configurational and prosodic aspects of speech separately. Tongue height also plays a role in determining the amount of anticipatory velum lowering in oral consonants, probably as a consequence of direct physical interference between the tongue and the soft palate.

Contrary to our expectations (Lubker, 1968 ; Fritzell, 1969; Bell-Berti, 1976, Bell-Berti et al, 1979), our rules did not need to include specific targets for the velum for vowels. Perhaps the importance of other factors in our data obscured the often observed relationship between velum height and vowel height. The influence of vowel height on velum height was observed only in utterances of nonsense syllables in our study. In contrast with previous observations (for German stops, Kohler, 1980), there was no obvious difference in velum behavior between fortis and lenis consonants.

The relative importance of suprasegmenta1 features on velum movement patterns seems to be speaker-dependent. As illustrated here, the behavior of the velum may differ, depending on whether the syllable is stressed or unstressed. It is possible that some of the differences between speakers A and B, such as the existence of the slow component, stem from different placements of the velum pellet. In any case, the extent of the influence of the suprasegmental factors relative to segmental factors seems to be of primary importance for understanding the differences between speakers. More data are clearly needed in order to optimize the feature set (involving [± stress] as well as [± strong], currently) and the rule systems or their common framework.

The approximation of movement patterns using a set of rules seems to be a valuable method for investigating complex behavior, such as the behavior of the velum in utterances of sentences. The report should be taken as an indication of possible rules that may be needed to account for some details of articulatory gestures.

Acknowledgements
The articulatory data used for this study were obtained in experiments conducted by Osamu Fujimura of AT&T Bell Laboratories with the cooperation of the University of Tokyo staff. We particularly thank Shigeru Kiritani, Research Institute of Logopedics and Pediatrics of the University of Tokyo, in this connection. Win Nelson and Joan Miller of AT&T Bell Laboratories developed the programs for analyzing the data, and I am very grateful to them for their help and kindness. And above all, I thank Osamu Fujimura for his constant help and attention during the course of this research. Marian Macchi of Bell Communications Research, in cooperation with him, assisted substantially in the preparation of this report.

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Table 1. Sentences used for data analysis

Figure captions:
(1) Ned went through some or the assigned material an unnecessary number of times.
(2) Ben announced that an innocent-seeming infant had nimbly nabbed most of the bananas.
(3) The training of the remnants of the regiment neared completion.
(4) A complement of militant nymphs promptly demanded amnesty.
(5) The ugly turtle collided with the collie.
(6) The Boston steersman dismissed the atlas.
(7) Don't disturb the anemic anemone after dinner.
(6) We need a leader with courage in distant places.
(9) Beb commands it: Beb commends it ; Beb commits it.
(10) Beb compacts it : Beb compels it : Beb competes it.
(11) If you displace the dummies, you'll have to disarrange the display.
(12) If you display the puppies, they'll be hard to displace.
(13) John made an attempt to remind Natasha of the fanbelt's condition.
Fig. 1. Lateral trajectories of pellets placed on the velum, the rear, mid, and front parts of the tongue surface, the lower tooth, and the lower lip, as displayed by an interactive analysis program (Miller and Fujimura, 1952). Broken lines indicating the outlines of the speech organs were added to a computer display. The bottom part of the display shows the speech signal envelope. The dotted crosses represent the pellet positions for the point in time corresponding to vertical dotted line through the speech signal. The three numbers at the top identify, from left to right, the utterance record number, beginning and ending frame numbers of the current display. The frame number for the current cursor position is shown below the sentence transcription to the right. The time interval between the frames is about 8.5 ms.

Fig. 2. Velum height (upper) and speech signal envelope (lower) time functions for the utterances given in phonetic transcription. The three pairs of traces represent three different utterances by the same speaker (speaker A):
(1) A complement of militant nymphs promptly demanded amnesty (32359).
(2) Ben announced that an innocent-seeming infant had nimbly nabbed most of the bananas (32357).
(3) John made an attempt to remind Natasha of the fanbelt's condition (32356).

Fig. 3. Velum height traces for utterances with utterances with non-nasal consonants (C) and utterances with nasal consonants (N) for speaker B. Time functions for different utterances are superimposed. The total duration of the utterances shown here is approximately 0.3 s. The vertical scale indicates velum height (relative to the maxilla) approximately in millimeter. In figures 3a and b, the time functions are lined up at the maximum and minimum velum height, respectively. Two cases of an oral consonant immediately surrounded by two nasal consonants (the final consonant of the first word in the sequences 'assigned material' and 'regiment neared') have not been plotted, since there is no peak in the velum tracings corresponding to the intermediate oral consonant.

Fig. 4. Velum height time function for oral consonants (C) for speaker B. In all cases, the first oral consonant is not immediately preceded by a nasal consonant. Here, the time functions in figure 3b are separated into two groups :
(a) C is followed by a vowel (V) and another consonant (C)
(b) C is followed by a vowel (V) and a nasal consonant (N).
The time functions in Figure 4h are further separated into two subgroups.
(c. d) the described in the text 'Configurational Environment').
In figure 4c, C has the feature value ([+strong]: in figure 4d, C has the feature value [- strong].

Fig. 5. Effect of stress on the velum lowering velocity in stressed versus unstressed CV sequences. The figure represents the vertical position of the velum pellet (vertical scale) as a function of time. The same scale has been used for the two speakers.

Fig. 6. Observed time functions (from top to bottom): speech signal lower lip height, tongue blade height, rear tongue height, and phonetic transcription for an utterance of the sentence 'A complement of militant nymphs promptly demanded amnesty'. Irrelevant portions of trace are suppressed to clarify the lip movement for the labial consonants (/p/ /m/, and /v/), the tongue tip movement for the consonant (/t/,/n/, /1/, and /r/), and the rear tongue movement for the consonant /k/. In the phonetic transcription, ≠ and # indicate word boundary and phrase boundary, respectively. The total duration from left to right is about 2.4 s.

Fig. 7. A preliminary algorithm for predicting the starting of velum lowering for speaker A, based on the information depicted in figure 6. The event in the box at the bottom of the figure deter- mine the starting time of the velum movement (see text). For example, in /CVN/, the velum tarts to lower at the acoustic release of the stop consonant.

Fig. 8. Velum movement predicted by the rules in figure 7. Solid lines enclose the speech waveform envelope for the three sentences shown in figure 2. Dotted lines, broken lines, and dot-dashed lines represent the blade, the lips, and the rear tongue pellets, respectively. The downward line above the speech envelope represents the lowering gesture whose onset has been determined using the rules described in figure 7.

Fig. 9. An algorithm for predicting the timing and movement velocity of velum raising for speaker A.

Fig. 10. Upward velum movements predicted by the rules in figure 9.

Fig. 11. Predicted velum movement for the slow component (see text), for the sentences in figure 10. Compare with figure 8.

Fig. 12. Predicted velum movement (dotted lines) superimposed on the observed velum movement time functions (solid lines) for three sentences produced by speaker A. The partial absence of a solid line for the middle sentence is due to pellet mis-tracking.

Fig. 13. Prediction algorithm for velum target position for speaker B.

Fig. 14. Prediction algorithm for velum movement velocity and p timing for speaker B.

Fig. 15. Predicted velum movement (dotted lines) and observed velum movement for six sentences for speaker B (table 1, sentences 1-6). The duration for each line is about 4.3 s.

(1) Ned went through some of the assigned material an unnecessary number of times (12446).
(2) Ben announced that an innocent-seeming infant had nimbly nabbed most of the bananas (12447).
(3) The training of the remnants of the regiment neared completion (12448).
(4) A complement of militant nymphs promptly demanded amnesty (12449).
(5) The ugly turtle collided with the collie (12451).
(6) The Boston steersman dismissed the atlas (12452).

Figure 1

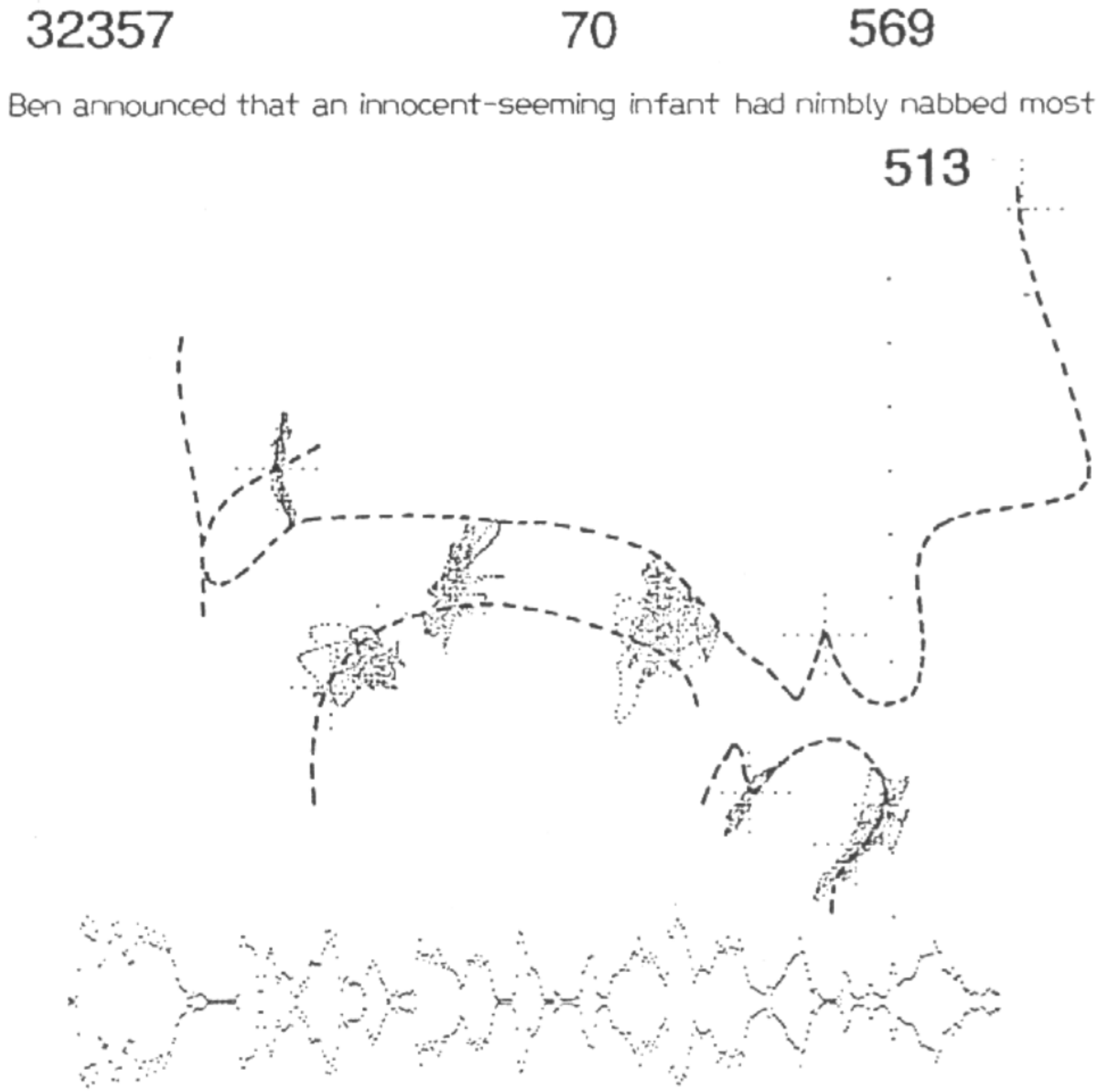
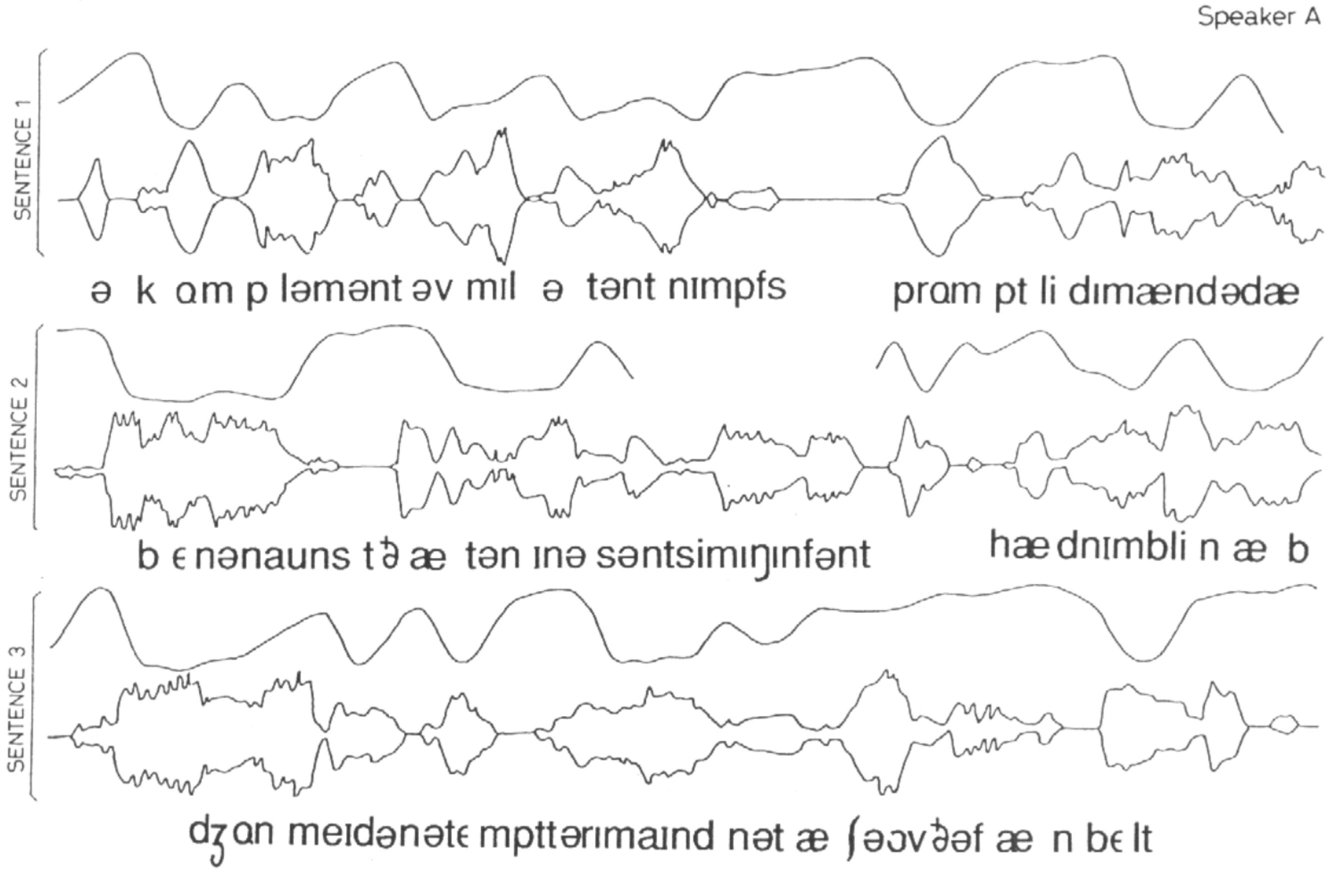

32357
70
569
Ben announced that an innocent-seeming infant had nimbly nabbed most
513

Figure 2:



Speaker A
SENTENCE 1
ə k ɑm p ləmənt əv mɪl ə tənt nɪmpfs
prɑm pt li dɪmændədæ
SENTENCE 2
b ɛ nənauns tð æ tən ɪnə səntsimiŋinfənt
hæ dnɪmbli n æ b
SENTENCE 3
dʒɑn meɪdənətɛ mpttərimaɪnd nət æ ʃəʊvðəf æ n bɛ lt

Figure 3:

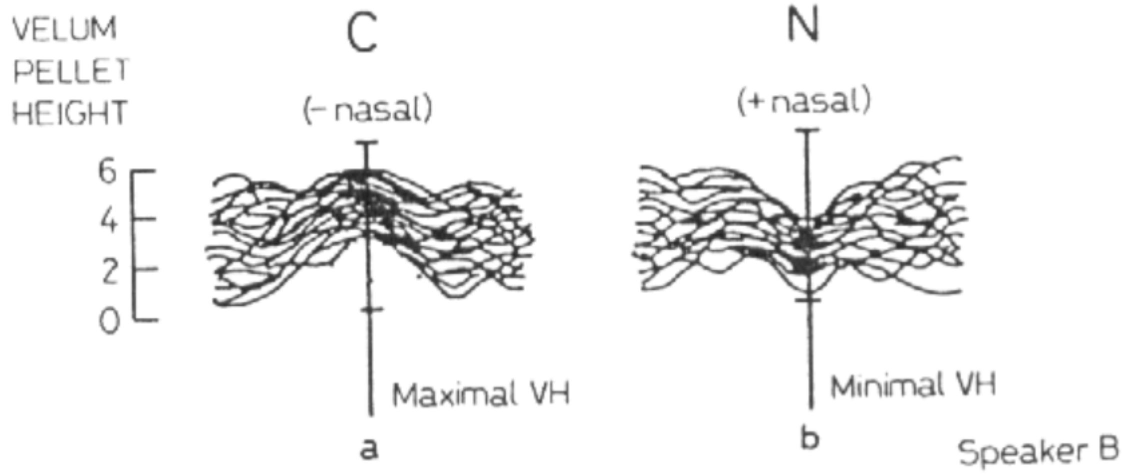
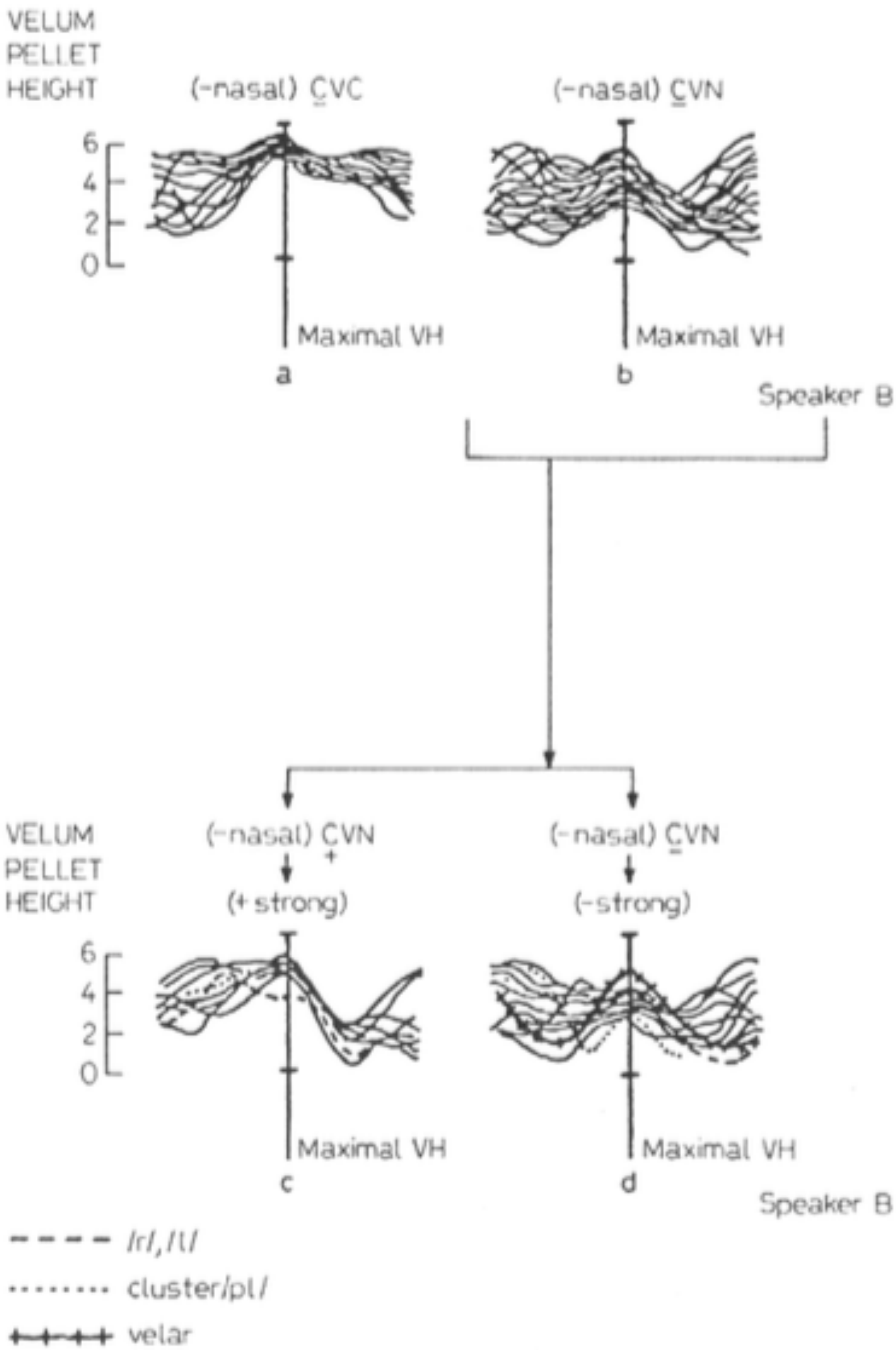

VELUM
PELLET
HEIGHT
6
4
2
0
C
(- nasal)
Maximal VH
a
N
(+ nasal)
Minimal VH
b
Speaker B

Figure 4 :



VELUM
PELLET
HEIGHT
(-nasal) CVC
(-nasal) CVN
6
4
2
0
Maximal VH
Maximal VH
a
b
Speaker B
VELUM
PELLET
HEIGHT
(-nasal) CVN
(+strong)
(-nasal) CVN
(-strong)
6
4
2
0
Maximal VH
Maximal VH
c
d
Speaker B
/r/, /l/
cluster /pl/
velar

Figure 5 :

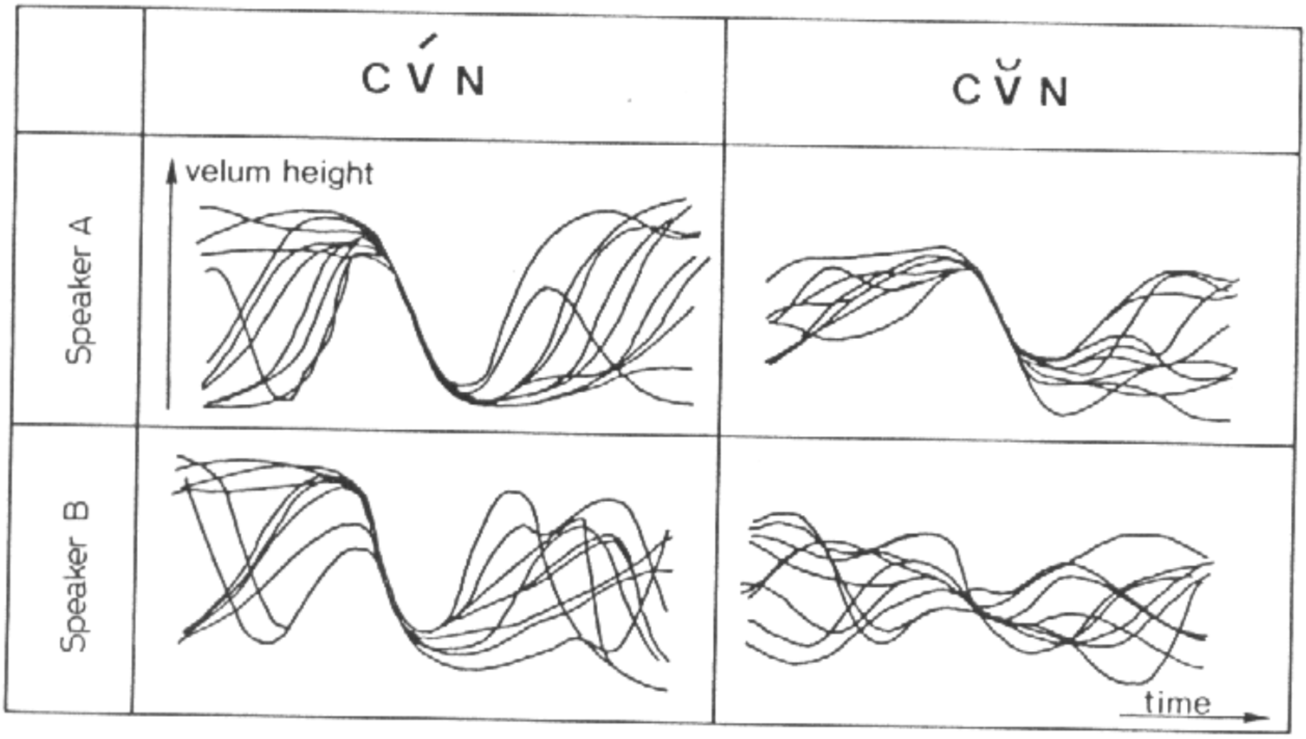


Figure 6 :

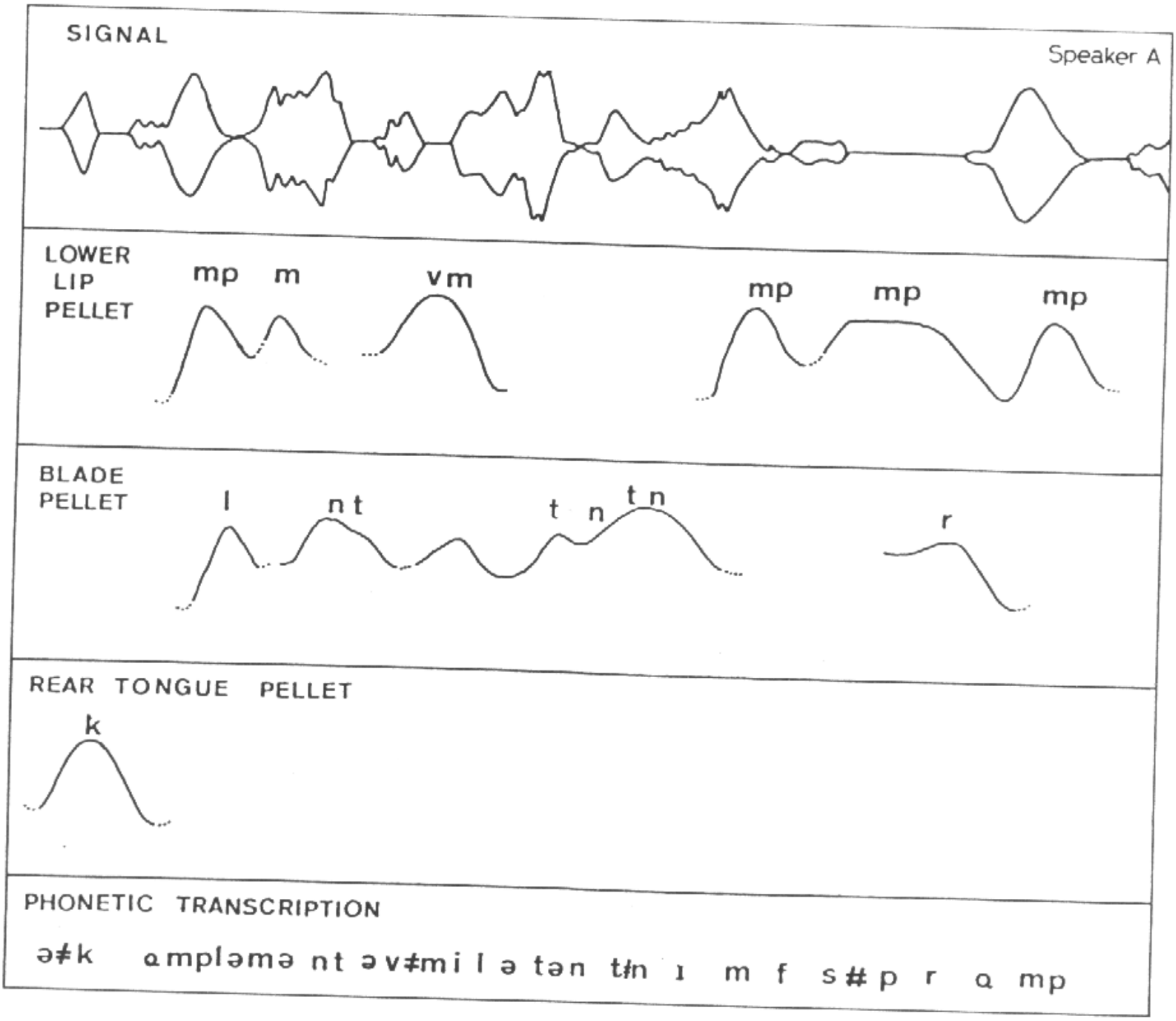

SIGNAL
Speaker A
LOWER LIP PELLET
mp m
vm
mp
mp
mp
BLADE PELLET
l
nt
t n
tn
r
REAR TONGUE PELLET
k
PHONETIC TRANSCRIPTION
ə≠k ɑmpləmə nt əv≠mi l ə tən t/n ɪ m f s#p r ɑ mp

Figure 7 :

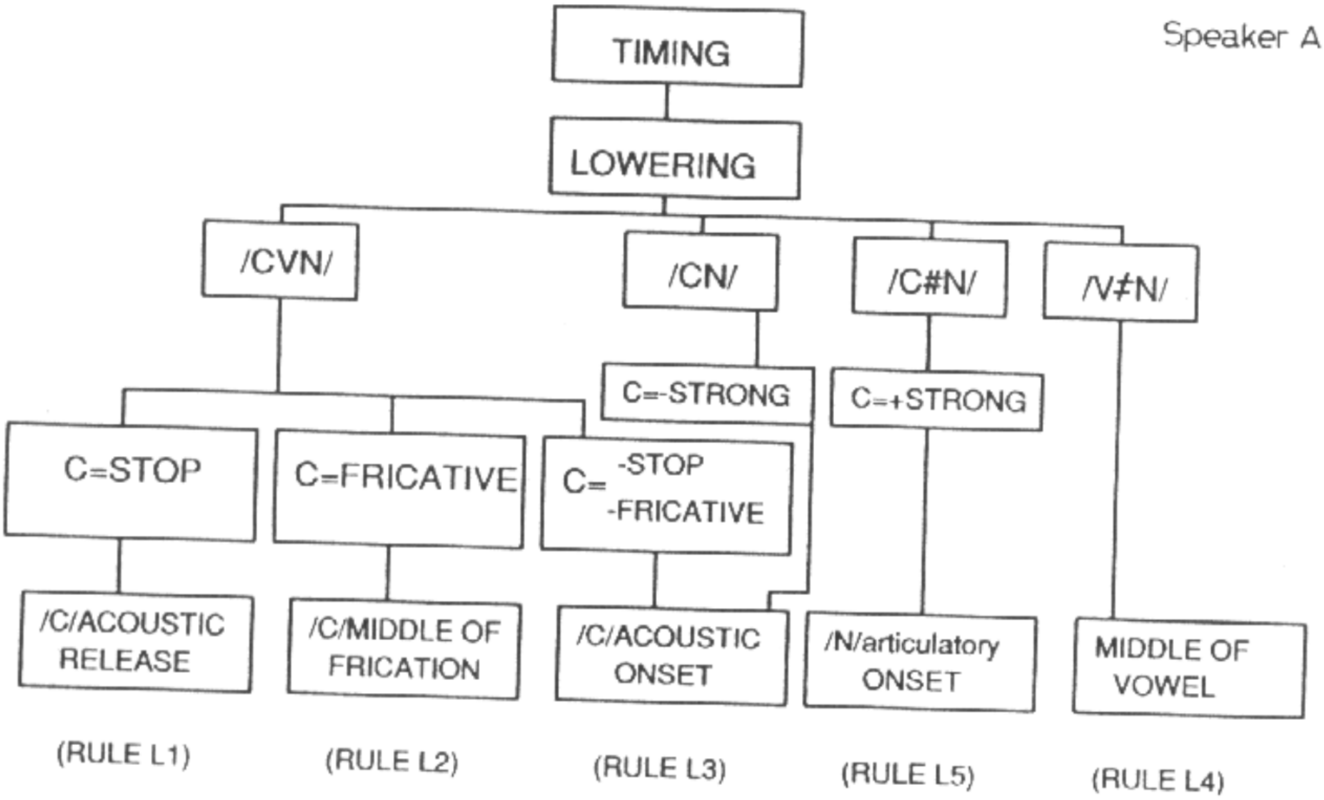

TIMING
Speaker A
LOWERING
/CVN/
/CN/
/C#N/
/V≠N/
C=-STRONG
C=+STRONG
C=STOP
C=FRICATIVE
C= -STOP -FRICATIVE
/C/ACOUSTIC RELEASE
/C/MIDDLE OF FRICATION
/C/ACOUSTIC ONSET
/N/articulatory ONSET
MIDDLE OF VOWEL
(RULE L1)
(RULE L2)
(RULE L3)
(RULE L5)
(RULE L4)

Figure 8 :

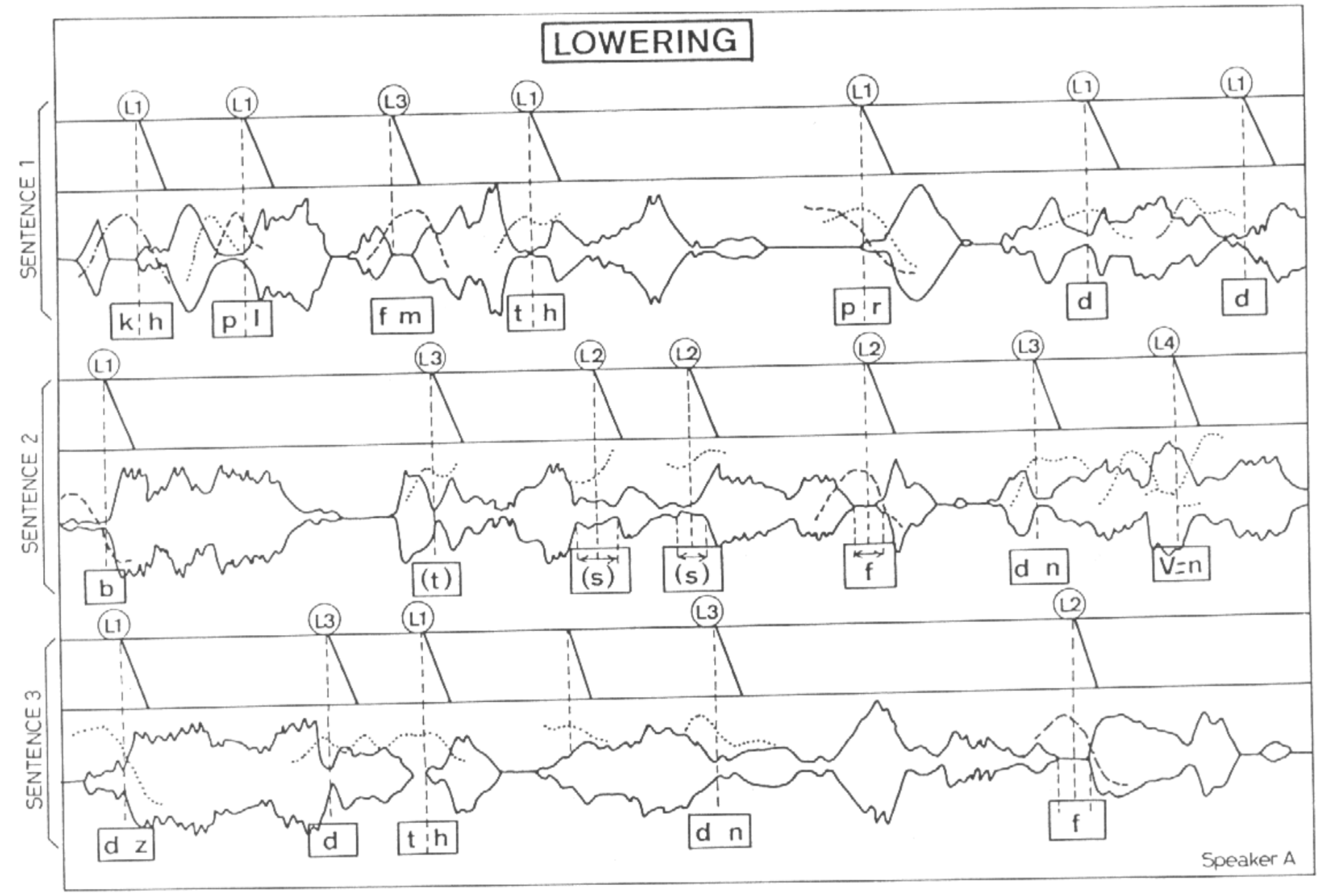

LOWERING
SENTENCE 1
L1
L1
L3
L1
L1
L1
L1
k h
p l
f m
t h
p r
d
d
SENTENCE 2
L1
L3
L2
L2
L2
L3
L4
b
(t)
(s)
(s)
f
d n
V=n
SENTENCE 3
L1
L3
L1
L3
L2
d z
d
t h
d n
f
Speaker A

Figure 9 :

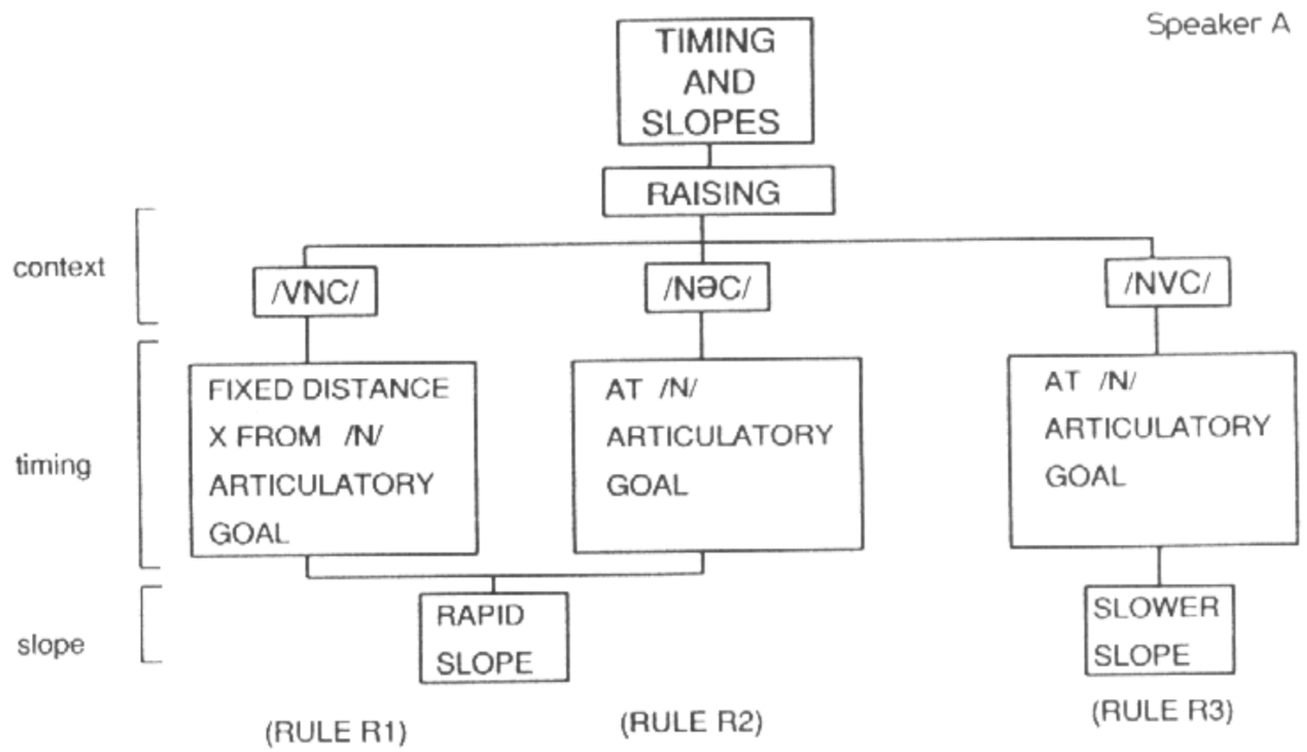

Speaker A
TIMING AND SLOPES
RAISING
context
timing
slope
/VNC/
/NəC/
/NVC/
FIXED DISTANCE X FROM /N/ ARTICULATORY GOAL
AT /N/ ARTICULATORY GOAL
AT /N/ ARTICULATORY GOAL
RAPID SLOPE
SLOWER SLOPE
(RULE R1)
(RULE R2)
(RULE R3)

Figure 10 :

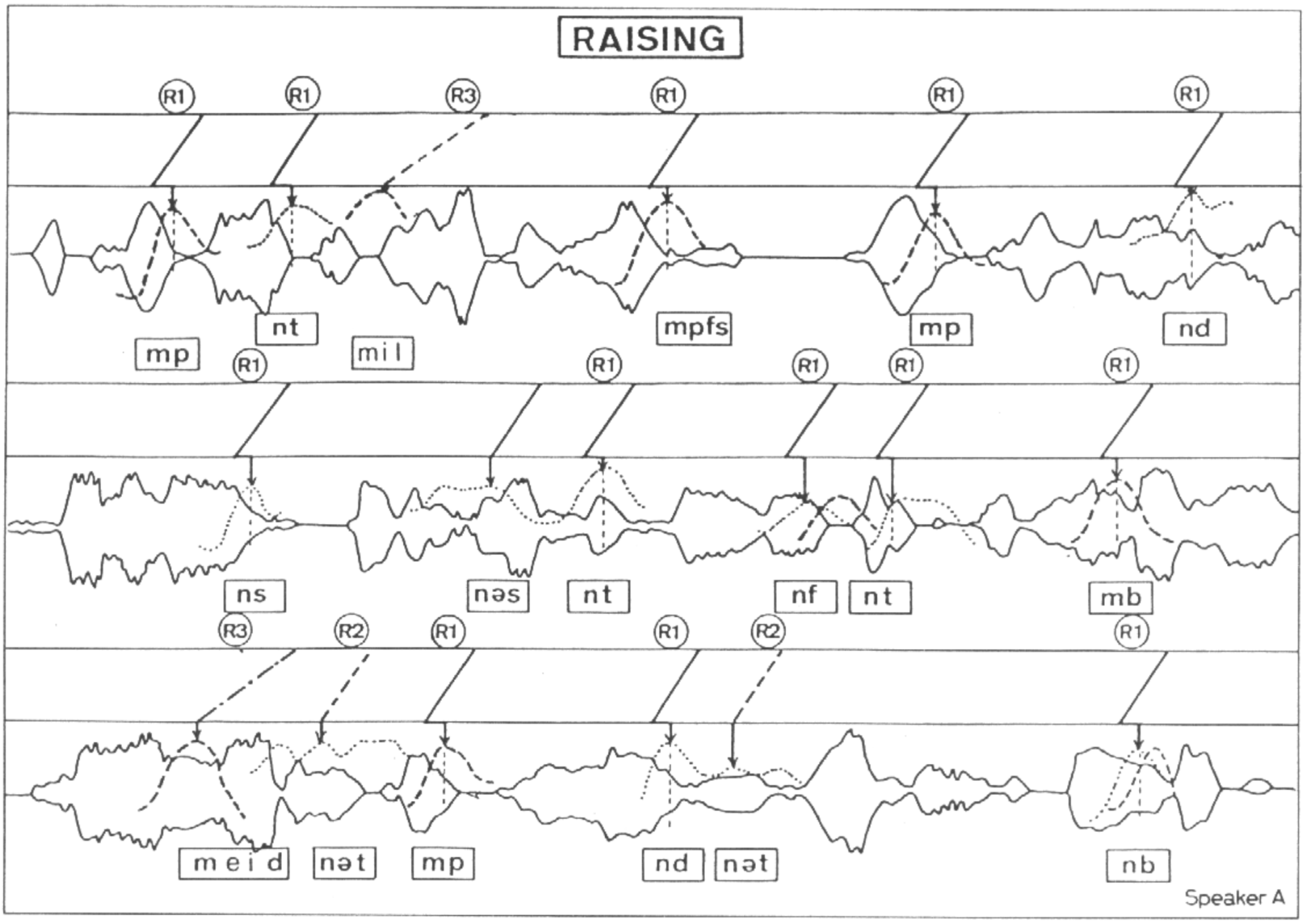

RAISING
R1
R1
R3
R1
R1
R1
mp
nt
mil
mpfs
mp
nd
R1
R1
R1
R1
R1
ns
nəs
nt
nf
nt
mb
R3
R2
R1
R1
R2
R1
meid
nət
mp
nd
nət
nb
Speaker A

Figure 11 :

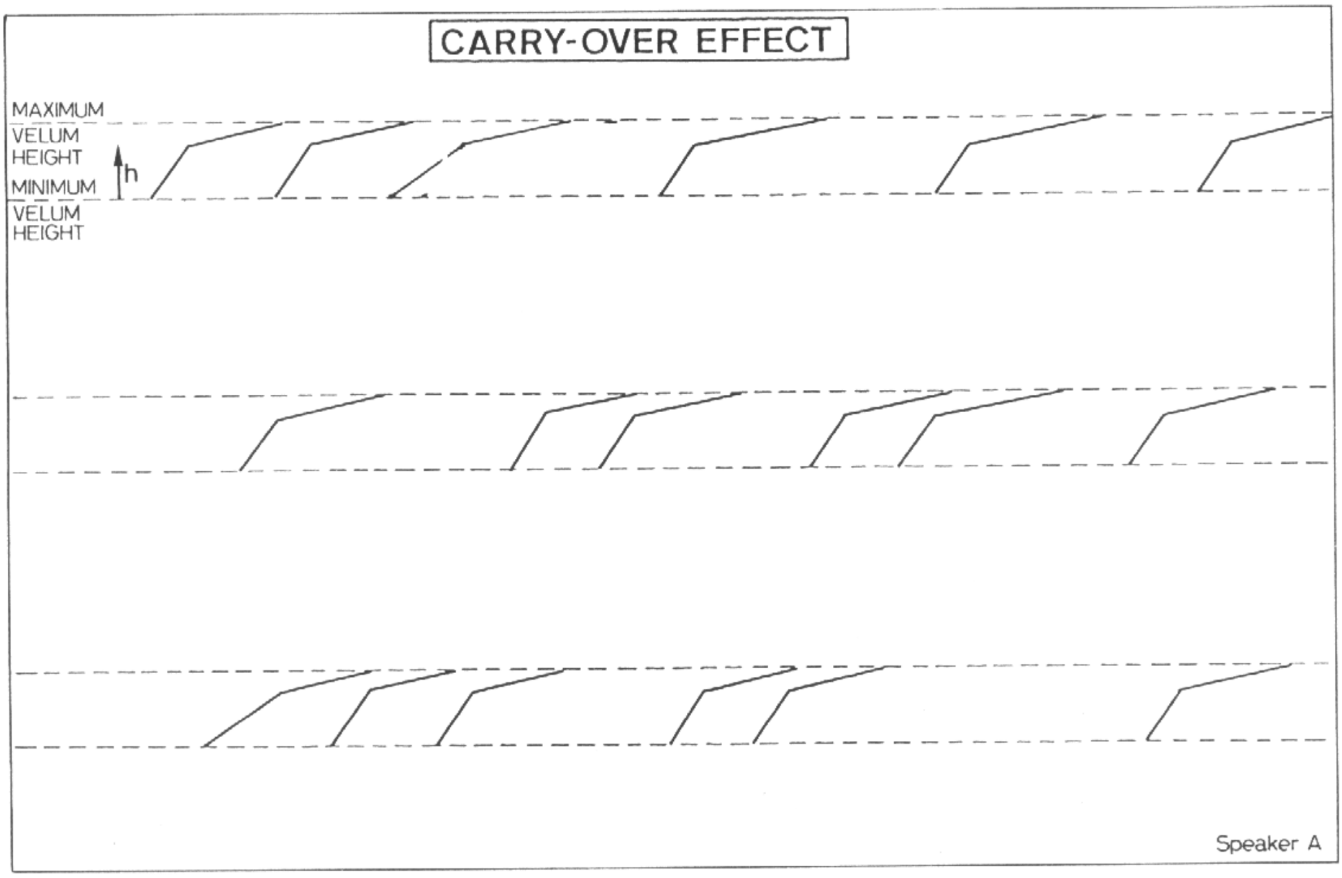

CARRY-OVER EFFECT
MAXIMUM
VELUM
HEIGHT
h
MINIMUM
VELUM
HEIGHT
Speaker A

Figure 12 :

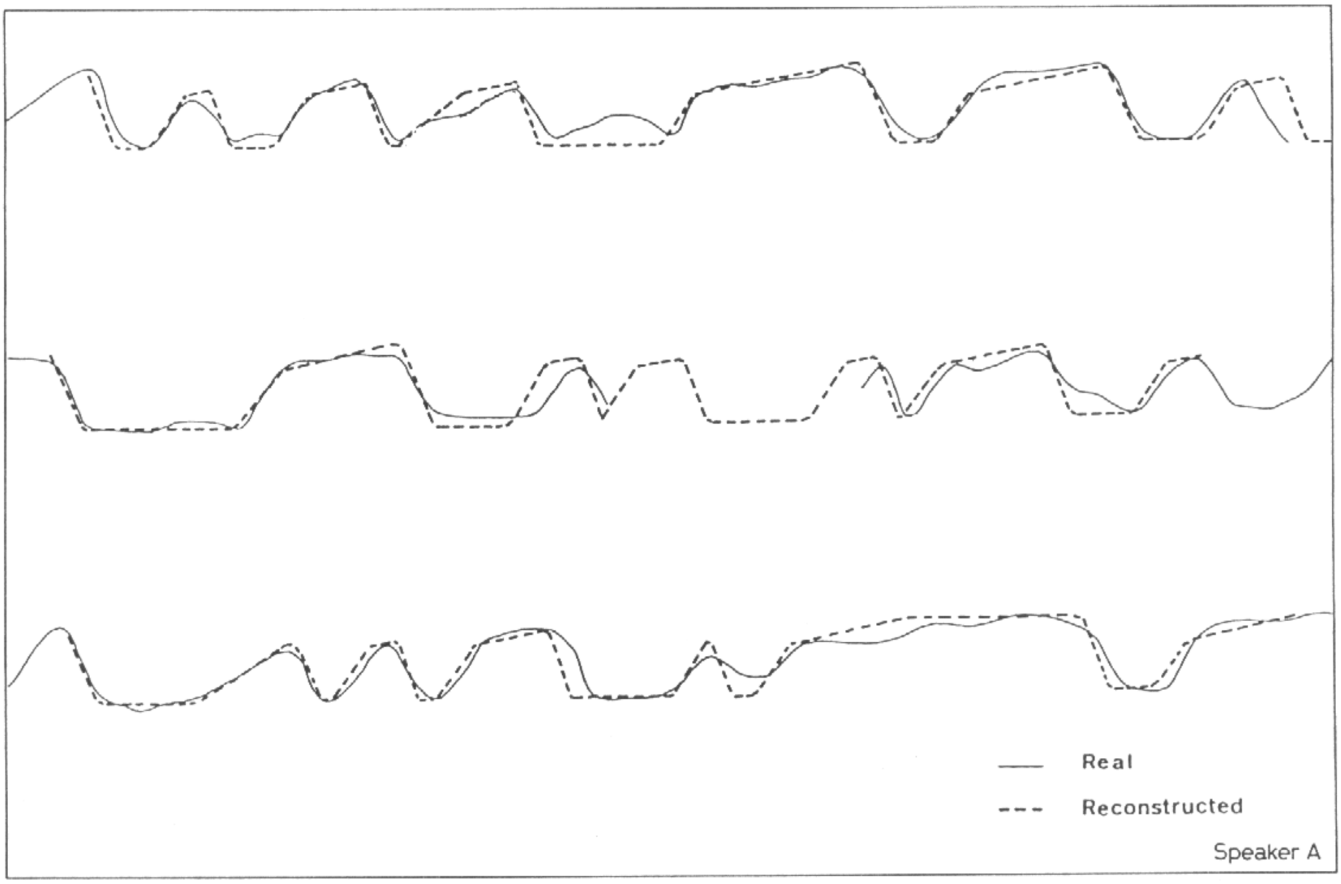
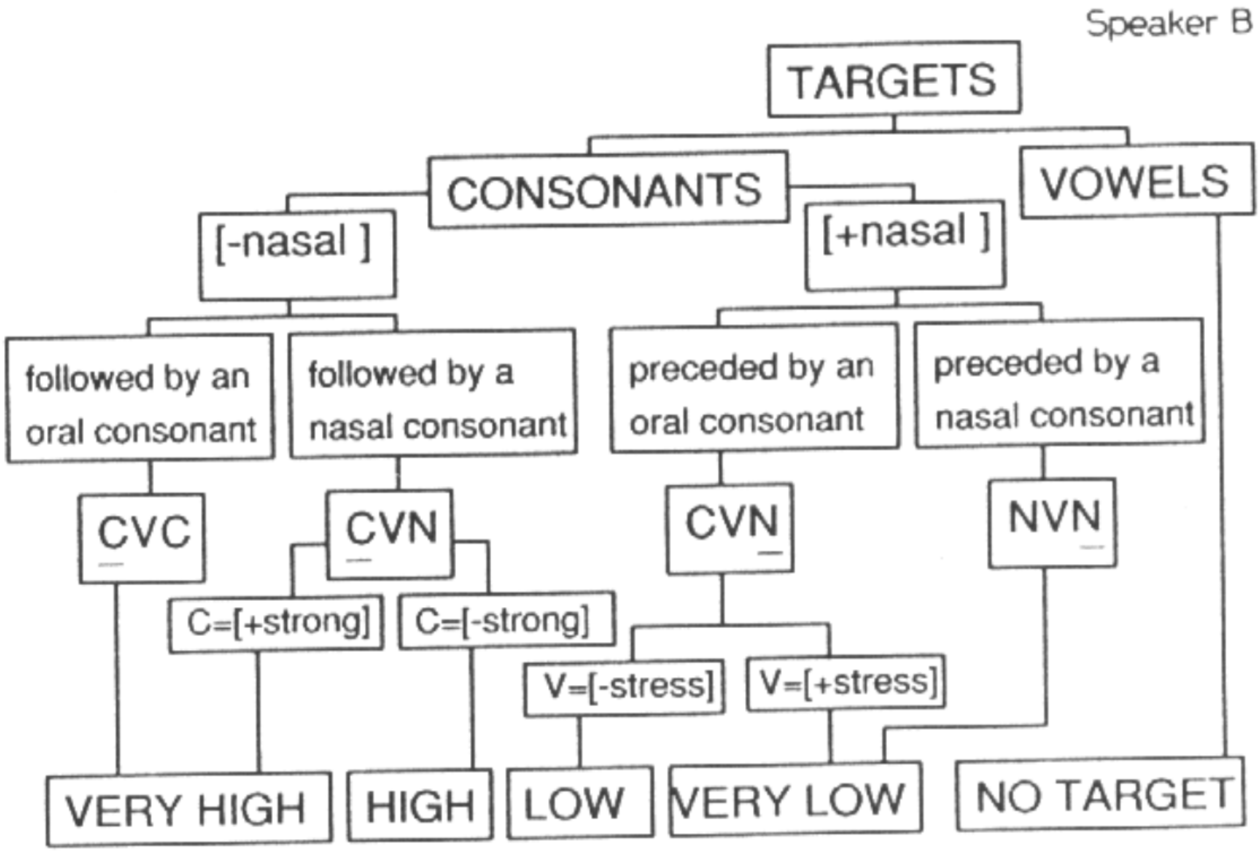


Figure 13 :



Speaker B
TARGETS
CONSONANTS
VOWELS
[-nasal]
[+nasal]
followed by an oral consonant
followed by a nasal consonant
preceded by an oral consonant
preceded by a nasal consonant
CVC
CVN
CVN
NVN
C=[+strong]
C=[-strong]
V=[-stress]
V=[+stress]
VERY HIGH
HIGH
LOW
VERY LOW
NO TARGET

Figure 14 :

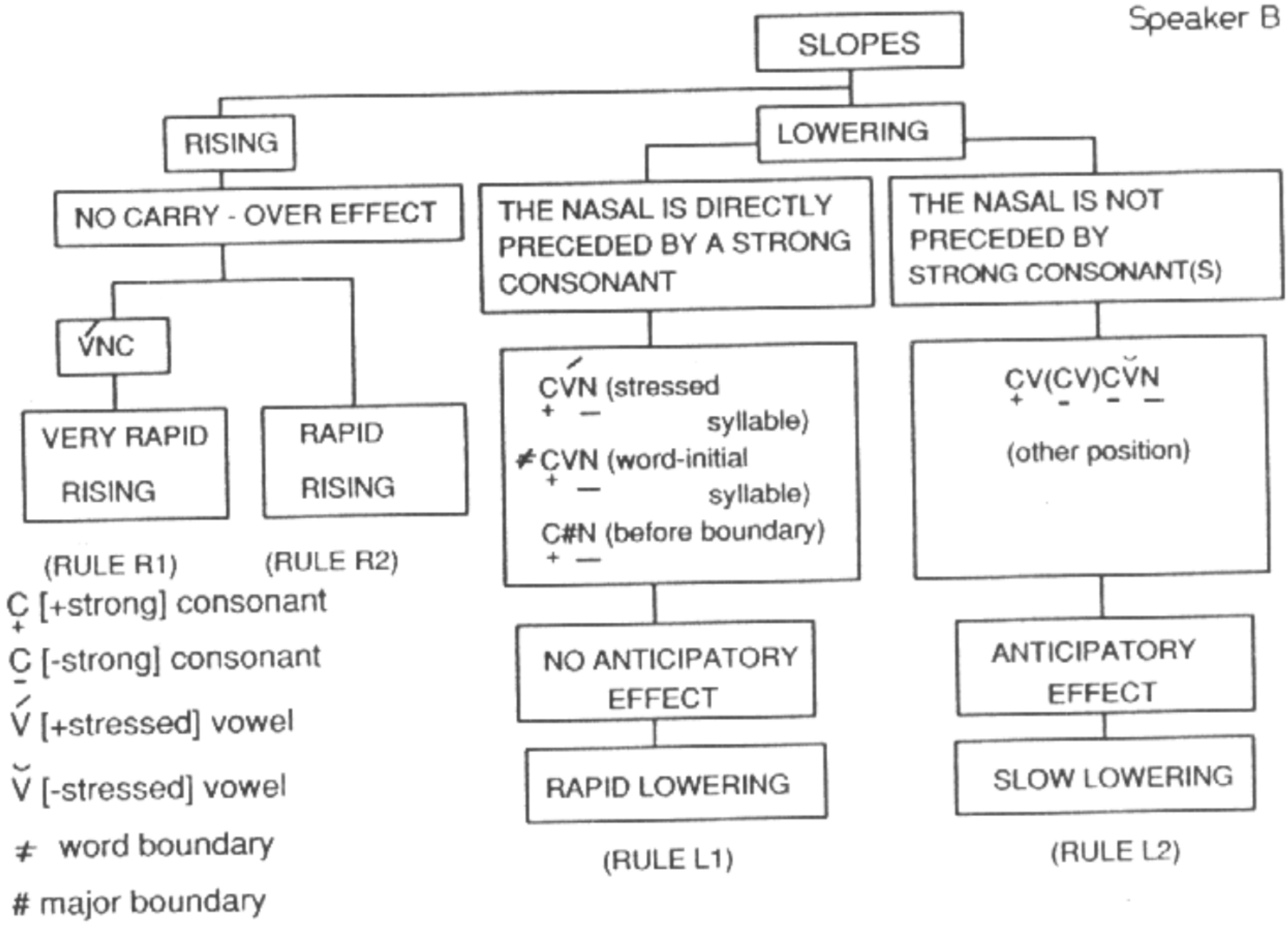
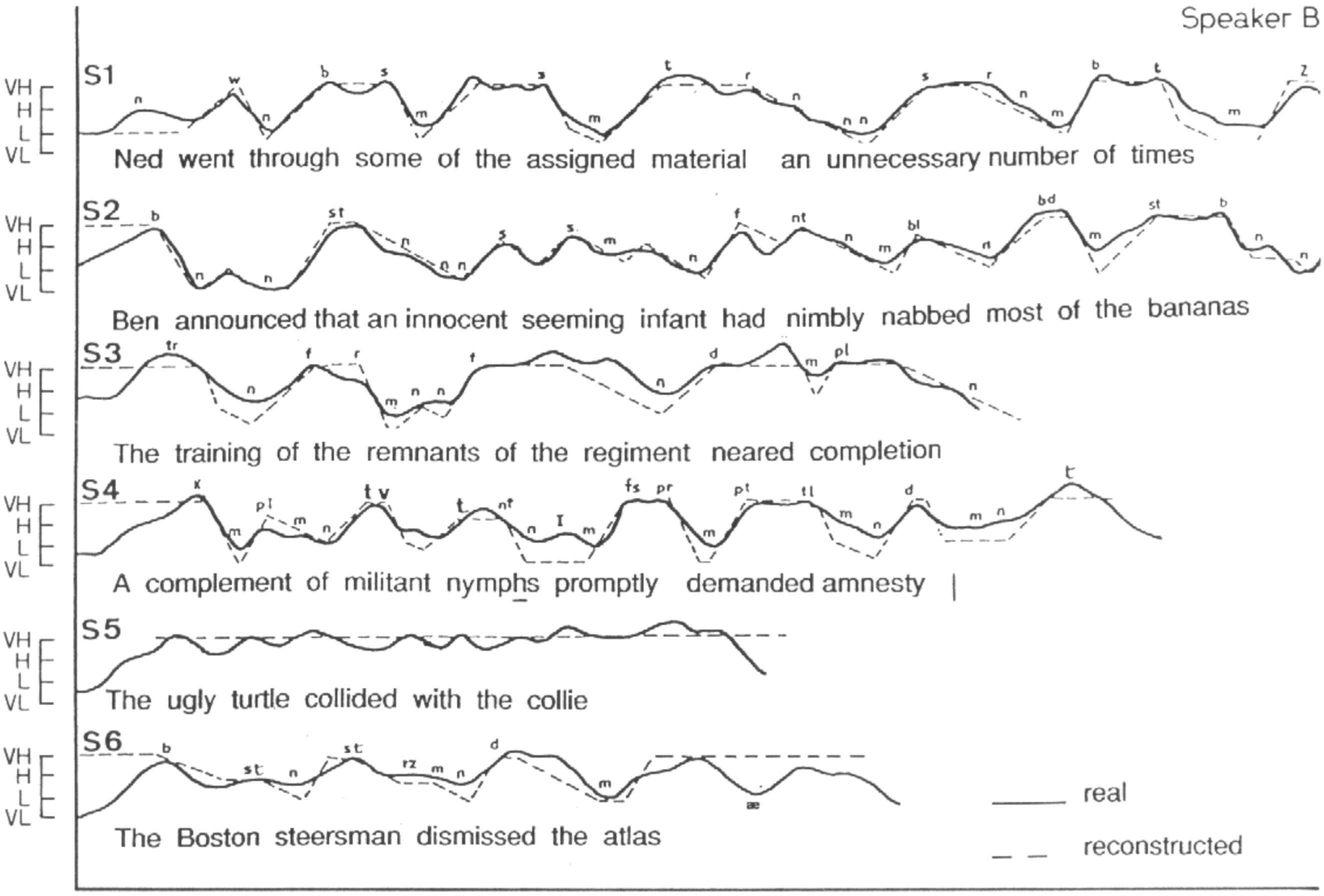

Speaker B
SLOPES
RISING
LOWERING
NO CARRY - OVER EFFECT
THE NASAL IS DIRECTLY PRECEDED BY A STRONG CONSONANT
THE NASAL IS NOT PRECEDED BY STRONG CONSONANT(S)
VNC
VERY RAPID RISING
RAPID RISING
(RULE R1)
(RULE R2)
CVN (stressed syllable)
≠CVN (word-initial syllable)
C#N (before boundary)
CV(CV)CVN
(other position)
NO ANTICIPATORY EFFECT
RAPID LOWERING
(RULE L1)
ANTICIPATORY EFFECT
SLOW LOWERING
(RULE L2)
C [+strong] consonant
C [-strong] consonant
V [+stressed] vowel
V [-stressed] vowel
≠ word boundary
major boundary

Figure 15 :


Speaker B
S1
VH
H
L
VL
Ned went through some of the assigned material an unnecessary number of times
S2
Ben announced that an innocent seeming infant had nimbly nabbed most of the bananas
S3
The training of the remnants of the regiment neared completion
S4
A complement of militant nymphs promptly demanded amnesty
S5
The ugly turtle collided with the collie
S6
The Boston steersman dismissed the atlas
real
reconstructed