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23 Supralaryngeal Declination: Evidence from the Velum

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INTRODUCTION

In several recent papers, Fowler and her colleagues (Fowler, 1988; Vatikiotis-Bateson & Fowler, 1988; Vayra & Fowler, 1992) have advanced an intriguing hypothesis—that there is a general "winding down" in speech that affects the upper articulators (e.g., the jaw and lips), in addition to fundamental frequency, acoustic amplitude, and subglottal pressure. The present study extends to another articulatory subsystem, the velum, the hypothesis that declination is a general phenomenon of speech production.

In contrast to supralaryngeal declination, fundamental frequency declination (the tendency of F_0 to fall over the course of a major syntactic unit or breath group) has received considerable attention in the phonetics and phonology literature (e.g., Breckenridge, 1977; Cohen, Collier, & 't Hart, 1982; Cooper & Sorenson, 1981; Pierrehumbert, 1979). The question of whether F_0 declination is actively controlled, long debated in the literature (see e.g., Lieberman, 1967; Cooper & Sorenson, 1981), was reconsidered by Gelfer (1987). Speech production necessitates regulation of muscular and recoil forces to control subglottal pressure and to extend expiration. Gelfer's results show that declining subglottal pressure over the course of a sentence can account, in large measure, for both a decline in F_0 and a concomitant decline in acoustic amplitude (see also 't Hart, Collier, & Cohen, 1990). Hence, declining F_0 and acoustic amplitude can be described as the passive consequences of the regulation of respiratory activity for speech.

To test the hypothesis that declination in speech affects supralaryngeal behavior, Fowler and her colleagues examined a number of articulatory and acoustic measures of vowels in English and Italian. Vayra and Fowler (1992) examined F_1 and F_2 frequency measures for vowels in the first and last syllables of bi- and tri-syllabic Italian pseudo-words produced by three speakers of Standard Italian. They found declination in the form of centralization for vowels at the extremes of the vowel triangle. That is, the open vowel /a/ became less open (F_1 decreased) and the close vowels, /i/ and /u/, became less close (F_1 increased). The F_2 measures indicated that there was also centralization along the front-back dimension: F_2 of front vowels decreased, and F_2 of back vowels increased. These results are consistent with the hypothesis that the latter part of an utterance is produced with increased relaxation or reduced energy.

Vayra and Fowler (1992) examined jaw opening as well as F_1 for the vowel /a/, produced by two other speakers of Standard Italian, in sequences of the form: 'BAbaba,' 'baBAba,' 'babaBA.' Their results showed a monotonic decrease in jaw opening and a corresponding decrease in F_1 for stressed vowels across the initial, medial, and final syllables of the sequences. The unstressed vowels, on the other hand, showed a V-shaped pattern, in which the least jaw opening and lowest values of F_1 occurred in the medial syllables. To determine whether jaw and formant changes over the course of the isolated trisyllables could be viewed as phrase- rather than word-level in origin, Vayra and Fowler compared the measures of the isolated trisyllables to measures of corresponding trisyllables embedded in a carrier phrase. They explained that word-level effects ought to be retained when the words are embedded in a larger context, while phrase-level effects ought to disappear or be considerably reduced. Their results were largely consistent with the interpretation that the original effects were phrasal in nature. That is, for one subject, F_1 and jaw declination occurred only in the trisyllables produced in isolation. For the second subject, F_1 declination occurred only in the isolated trisyllables, whereas jaw declination occurred in both kinds of productions, but was reduced in magnitude in the sentence as compared with the isolated word condition.

A separate study by Vatikiotis-Bateson and Fowler (1988) focused entirely on sentence-level effects; in this case, measures were made of changes over the entire span of a sentence, rather than of changes across a word produced in isolation or embedded in a sentence. This study examined a variety of kinematic measures of lip opening in reiterant sentences (CVCVCV...) produced by speakers of English. They observed weak, but consistent, declination in the extent, peak velocity, and duration of opening and closing gestures over the course of the utterances.

Unfortunately, this sentence-level study did not include measures of corresponding F_0 data. While Gelfer's study showed parallel functions for subglottal pressure and F_0, no previous study of sentence-level declination has compared measures of F_0 and articulation or formant frequencies. But F_0 and acoustic amplitude data were obtained by Vayra and Fowler (1992) for the Italian trisyllables, described above, in which jaw and formant frequency declination were observed. Of interest was their finding of a divergence between the patterns of declination for the supralaryngeal measures, on the one hand (i.e., jaw and formant frequency), and the respiratory-laryngeal measures, on the other (i.e., F_0 and acoustic amplitude). That is, whereas declination of F_1 and jaw opening had been largely restricted to stressed vowels, declination of F_0 and acoustic amplitude occurred for both stressed and unstressed vowels. This suggests that while declination may occur across different components of the speech production mechanism, its occurrence may be manifested differently from one component to the other.

The present work reflects our interest in extending the hypothesis that declination is a general phenomenon in speech production to another articulatory subsystem, the velum. Finding declination for the velum would further support earlier studies indicating that the velum participates in the prosodic organization of speech. Previous studies have shown, for example, robust effects of stress (Krakow, 1989, 1993; Vaissière, 1988) and speaking rate (Bell-Berti & Krakow, 1991; Kent, Carney, & Severied, 1974; Krakow, 1993; Kuehn, 1976) on the velum. Data collected for other purposes (Bell-Berti & Krakow, 1991) revealed what appeared to be declination in peak velum positions for oral consonants over the course of individual sentences, but the sequences were not appropriately designed to test for declination systematically. Hence, we decided to explore this issue in more detail with more suitably designed sequences. Guided by the studies described above, we investigated a number of specific issues.

We compared initial with final velar peaks in both natural and reiterant speech, to answer the question of whether there was declination from the first to the last syllables of the sentences, as has been reported for fundamental frequency. Since, in measuring F_0 early and late in a sentence, researchers have sought stability in one or the other endpoint and/or in the total amount of declination in sentences of varying length, we looked for such stability in our velar measures. We asked whether initial or final velar peaks, or the difference between them, was influenced by sentence length. Conceivably, examination of initial and final measures might provide little insight regarding declination throughout the utterance. We therefore compared measures of medial velar peaks (from the reiterant speech samples) to determine whether declination occurred throughout individual sentences, and whether the nature of the decline, if observed, changed over the time course of a sentence. Measurement of medial peaks also provided information on the relation between stress and declination in a manner that initial and final peaks did not. That is, the initial and final peaks occurred in stressed syllables whereas the medial peaks occurred in both stressed and unstressed syllables. Looking across medial sentence positions, we were able to compare declination in stressed and unstressed syllables, and to determine whether the contrast between the stressed and unstressed syllables in a word changed as a function of the word's position in a sentence. Finally, to determine whether the relation between stress and position in sequence might distinguish velar (i.e., supralaryngeal) declination from F_0 declination (as Vayra and Fowler observed for formant and jaw declination vs. F_0 declination), we compared our measures of velar peaks to corresponding measures of F_0 peaks in stressed and unstressed syllables variously positioned in our sentences.

Methods

Data Collection

Subjects. Three native speakers of American English served as subjects. One of the subjects (S1) was a co-author. No subject had a history of speech or hearing impairment.

Stimuli. The utterance list was devised to enable us to measure velar peaks over the course of individual sentences ranging in length from three to nine syllables. We used both natural and reiterant sentence stimuli (Table 1), making most of our measures on the latter, to avoid the confounding of segmental and prosodic effects on the velum. To ensure that the reiterant sentence data at least resembled the natural sentence data, we did make a number of measures on both. We also attempted, to the extent possible, to have our natural sentences make sense and yet vary minimally with respect to consonant segments. In this experiment, we chose to look at velar peaks. Among speech sounds, obstruents require the highest positions of the velum. Thus, all of the syllable-initial consonants in our study were obstruents. In our natural sentences, most were /s/. In our reiterant sentences, all were /t/ (the reiterant syllable was "ten").

TABLE 1. *Stimuli.*

Natural speech sentences	# of syllables
Sue saw Sid.	3
Suzy saw Sid.	4
Suzy saw sad Sid.	5
Suzy saw sexy Sid.	6
Suzy saw sad sexy Sid.	7
Suzy saw sexy sassy Sid.	8
Suzy saw sad sexy sassy Sid.	9
reiterant syllable: "ten"	

Instrumentation. The time-varying vertical position of the velum was tracked with the Velotrace (Horiguchi & Bell-Berti, 1987). The device, which is inserted through the nose, consists of three major parts: a curved internal lever that rests on the nasal surface of the velum, an external lever that remains in full view outside of the nose, and a push rod (carried on a thin support rod) that connects the internal and external levers. Movements of the velum result in changes in the angle of the internal lever with respect to its fulcrum that are reflected in corresponding angular movements of the external lever; the levers are connected so that when the internal lever is raised (by a raising movement of the velum), the external lever moves toward the subject. Hence, measurement of the movement of the external lever in the x-dimension provides information on the y-dimension of velum displacement. The external lever of the Velotrace is considerably longer than the internal lever, so the obtained displacements are larger (about twice as large) than the actual displacements.

An optoelectronic tracking system (Kay, Munhall, Vatikiotis-Bateson, & Kelso, 1985) was used to track the movements of light-emitting diodes (LEDs) mounted on the external lever and on the fulcrum of the Velotrace (the latter, for reference). The positions of the LEDs in the midsagittal plane were tracked by a position-sensitive detector, and the reference signal was subtracted from the data signal in order to factor out head movement. Acoustic recordings were obtained simultaneously with the movement recordings. All signals were recorded onto a 14-channel FM data recorder.

Procedure. The natural sentences were printed on individual file cards and shown to subjects one at a time. Each reiterant sentence was produced with the same number of syllables as its natural speech model (see Liberman & Streeter, 1978). Subjects were instructed to produce the natural sentence first, followed by the matched reiterant sentence. Subjects produced 12 randomized repetitions of each of the seven natural-reiterant sentence pairs. A small number of tokens had to be deleted from analysis because they were truncated during recording.

Data Analysis

Measurement. We measured the syllable-initial velar peaks for the first and last syllables of both the natural and reiterant sentences. For the natural sentences, we measured the velar peaks for /s/ in "Sue" or "Suzy" and "Sid." For the reiterant sentences, we measured the velar peaks for /t/ in all of the syllables. Measurements of the first and last syllable-initial peaks in each sentence enabled us to see how well the reiterant speech was modeled on the natural speech. One of the measures used to compare the two was the interval between the first and last peaks, as a function of the number of syllables in each sentence. Figure 1 reveals that the natural and reiterant sentences were of similar duration.

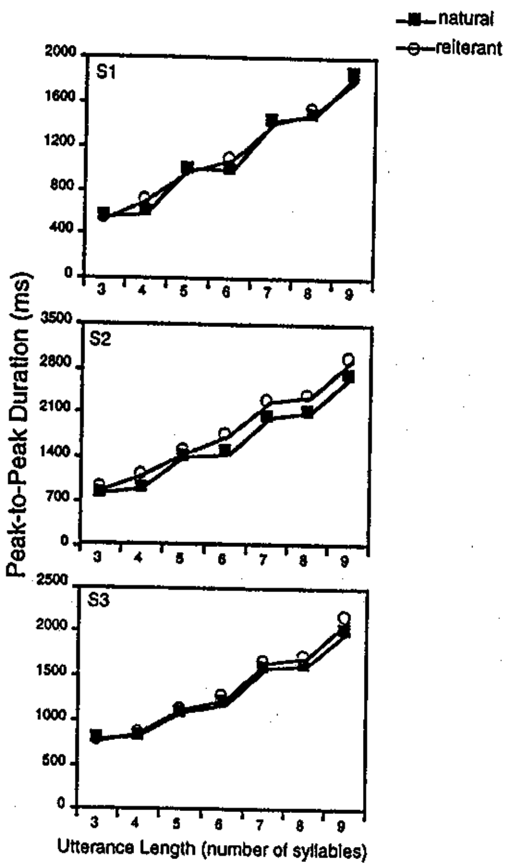

FIGURE 1. Mean intervals between the first and last syllable-initial velar peaks as a function of the number of syllables in each sentence. Natural sentences are plotted with solid squares, and the corresponding reiterant sentences, with open circles. Data for S1, S2, and S3, are shown at the top, middle, and bottom, respectively.

The other comparisons between natural and reiterant sequences involved the declination measures, which are described in the results section, below. In order to examine the interaction of stress with position in a sentence on velar vs. F_0 data, we also measured peak F_0 for the reiterant stressed and unstressed syllables of "Suzy," "sexy," and "sassy."

Results

Initial vs. Final Positions: Velar Data

Figure 2 shows initial and final peak values for natural and reiterant sentences. (We remind you that our figures are derived from velar movements as monitored with the Velotrace, which magnifies those movements about two-fold.) Testing for declination from the beginning to the end of the sentences, we first ran a three-way ANOVA that examined the variables: sentence *position* (initial vs. final peak), sentence *length* (3,4,5,6,7,8,9 syllables), and sentence *type* (natural vs. reiterant). The results of this ANOVA are shown in Table 2.

The results revealed a significant main effect of *type* for each of the three subjects reflecting the fact that natural peaks were consistently higher than reiterant peaks. This finding seems largely to be a function of the fact that the reiterant speech contained nasal segments (which display lower velar peaks because of coarticulation) while the natural speech did not. The effect may also reflect other segmental differences between the two types of sentences (e.g., syllable-initial /s/ vs. /t/). The results also showed a main effect of *position* (i.e., initial vs. final peaks) for the three subjects, supporting the notion that there is declination of velar movements from the beginning to the end of sentences.

For S2, the main effect of *length* was not significant and there were no significant two- or three-way interactions of factors. Hence, only *position* and *type* showed a significant influence on peak velum position. For S1 and S3, there was a main effect of *length*, suggesting that velar peaks were affected by the number of syllables in the sentence. However, both of these subjects also showed significant interactions that likely bear on the nature of this main effect. A significant *position* × *length* interaction for both S1 and S3 meant that we needed to examine the effect of *length* on first vs. last peaks. For S3, the difference between first vs. last measures, examined in an analysis of simple main effects, showed significance for sentences of each *length* ($p < 0.01$), except those of five syllables, which approached significance ($p = 0.06$). For S1, the effect was significant for all but the shortest *length* (3 syllables: $p > 0.1$; 4 - 5 syllables: $p < 0.05$; 6 - 9 syllables: $p < 0.01$—see Table 3, for the detailed results). These results suggest that declination, as assessed by comparisons between the first and last syllable in a sentence, is observed across a range of sentence lengths for all three subjects.

To clarify the nature of the interaction between *length* and *position*, we also ran an analysis of simple main effects comparing first vs. last peaks separately for the reiterant and natural speech sentences. The effect of sentence *length* on initial measures was not significant for either S1 or S3 (S1: [$F(6,298) < 1.0$, $p = 0.7893$]; s3: [$F(6,308) = 1.02$, $p = 0.4127$]), while the effect of sentence length on final measures was significant for both (S1: [$F(6,298) = 5.20$, $p < 0.0001$]; S3: [$F(6,308) = 5.87$, $p < 0.0001$]). This means that for these subjects, the main effect of *length* stems from effects on final measures alone.

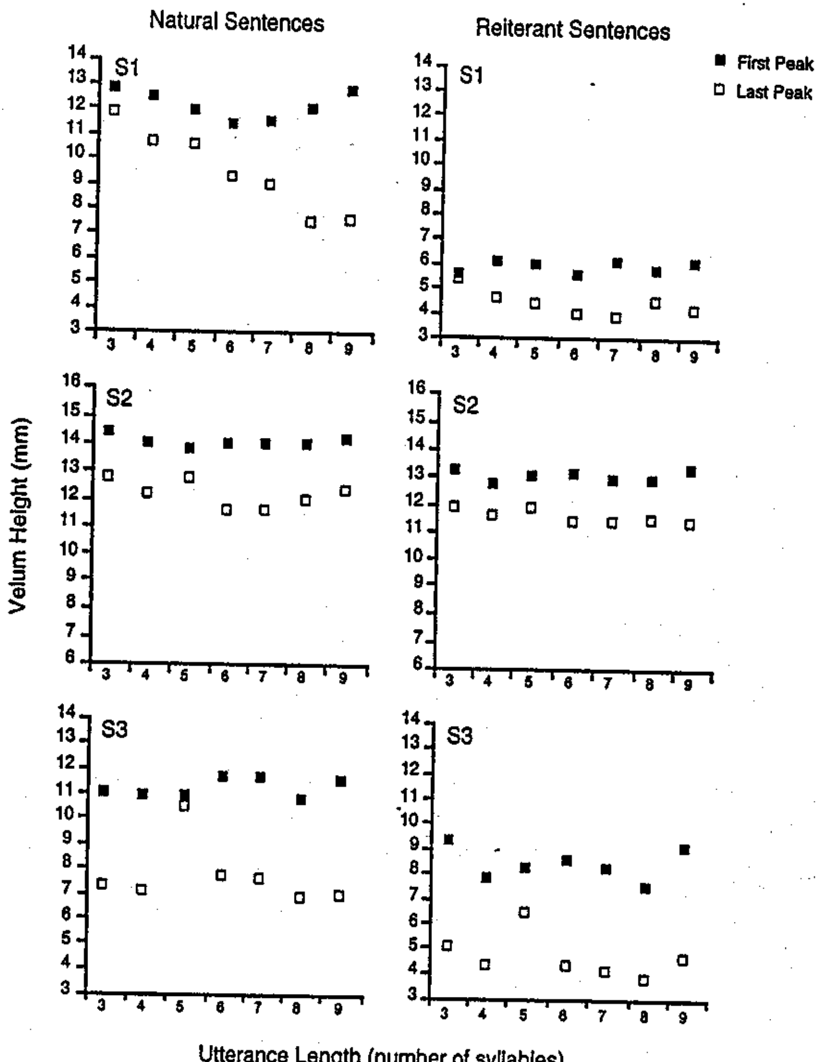

FIGURE 2. Mean values of velum height at the first (solid squares) and last (open squares) syllable-initial peaks in the natural (left) and reiterant (right) sentences as a function of the number of syllables in each sentence. Data for S1, S2, and S3, are shown at the top, middle, and bottom, respectively.

TABLE 2. *Results of three-way ANOVA on the effects of position, length, and type on peak velar positions.*

Subject	S1			S2			S3		
variable	*F*	(df)	*p*	*F*	(df)	*p*	*F*	(df)	*p*
position	76.9	(1,298)	<0.0001	31.18	(1,303)	<0.0001	245.81	(1,308)	<0.0001
length	3.2	(6,298)	<0.01	0.32	(6,303)	NS	3.48	(6,308)	<0.01
type	586.72	(1,298)	<0.0001	6.92	(1,303)	<0.01	163.34	(1,308)	<0.0001
position × type	6.12	(1,298)	<0.05	0.43	(1,303)	NS	0.34	(1,308)	NS
length × type	1.55	(6,298)	NS	0.05	(6,303)	NS	0.82	(6,308)	NS
position × length	2.52	(6,298)	<0.05	0.18	(6,303)	NS	3.4	(6,308)	<0.01
position × type × length	1.42	(6,298)	NS	0.06	(6,303)	NS	0.26	(6,308)	NS

Because there was no significant interaction of *length* with *type* for either subject, we collapsed the measures for natural and reiterant sentences at the final position to look at the nature of *length* effects in final positions for the two subjects. We observed a negative correlation between sentence *length* and the final peak that was significant for S1 [$r = -0.264$, $p < 0.001$] but not for S3 [$r = -0.126$, $p > 0.1$]. Thus, for S1, increasing *length* resulted in increasingly lower final velar peaks. For S3, who showed an effect of *length* on final consonants, the nature of that effect is not clear.

Only S1 showed another significant interaction, that of *position × type*, meaning that the first vs. last peak difference was influenced by their occurring in natural or reiterant sentences. Testing the simple main effect of *position* (i.e., first vs. last) for the natural [$F(1,298) = 61.89$, $p < 0.01$] and then for the reiterant sentences [$F(1,298) = 20.24$, $p < 0.01$], we found that while both showed higher initial than final peaks, the difference was larger for the natural sentences (mean 12 mm vs. 9.43 mm) than for the reiterant sentences (mean 5.82 mm vs. 4.36 mm).

In studies investigating the decline of F_0, researchers have measured endpoint values, as we have just described for the velum; they have also examined the magnitude of the difference between the two endpoint values. Therefore, to complete our examination of the relation between sentence length and velum height, we ran a two-way ANOVA on the effects of sentence *length* (3-9 syllables) and sentence *type* (natural/reiterant) on the difference in velum height from the first to the last syllable-initial peak (Table 4).

The effect of sentence *type* on the difference in velum position was significant only for S1 and S2, but the effect was not consistent across subjects: on average, S1 showed greater differences for natural than reiterant sentences, whereas S2 showed greater differences for reiterant than natural sentences. The effect of *length* was significant for all three subjects. To determine whether this latter effect reflected greater declination for longer sentences, we tested the correlation between sentence *length* and the measured difference between the first and last peaks.

TABLE 3. *Results of an analysis of the simple main effect of measurement position on peak velar height at each sentence length.*

Subject:	S1			S3		
number of syllables	*F*	(df)	*p*	*F*	(df)	*p*
3	0.89	(1,298)	NS	42.61	(1,308)	<0.0001
4	6.64	(1,298)	<0.05	35.08	(1,308)	<0.0001
5	5.82	(1,298)	<0.05	3.44	(1,308)	NS
6	9.01	(1,298)	<0.01	45.91	(1,308)	<0.0001
7	15.10	(1,298)	<0.001	45.15	(1,308)	<0.0001
8	22.69	(1,298)	<0.0001	40.14	(1,308)	<0.0001
9	30.36	(1,298)	<0.0001	53.63	(1,308)	<0.0001

TABLE 4. *Results of a two-way ANOVA on the effects of sentence length and type on the change in velar position from the earliest to the latest measurement point.*

Subject:	S1			S2			S3		
variable	*F*	(df)	*p*	*F*	(df)	*p*	*F*	(df)	*p*
length	9.98	(6,149)	<0.0001	3.60	(6,152)	<0.01	7.02	(6,154)	<0.0001
type	24.01	(1,149)	<0.0001	88.11	(1,152)	<0.0001	0.69	(1,154)	NS
length × *type*	5.55	(6,149)	<0.0001	0.42	(6,152)	NS	0.53	(6,154)	NS

For S2 and S3, we collapsed measures from the reiterant and natural sentences, while for S1 (who showed an interaction between the two factors), we did not. (For S1 natural, r = –0.684, $p < 0.001$; for S1 reiterant, r = –0.229, $p < 0.05$; for S2, r = –0.189, $p < 0.05$; for S3, r = –0.156, $p < 0.05$). Clearly, the difference measures captured something that the measures of first and last peaks taken separately did not. Nonetheless, these correlations, while significant, were weak, with the exception of S1's natural sentence data.

Medial Positions: Velar Data

A reduction in peak velum height from the beginning to the end of a sentence is consistent with the notion of decreasing energy from start to finish in a sentence, as higher velum positions are normally associated with increased activity of the levator palatini (see Bell-Berti, 1993). However, the notion that the phenomenon of declination occurs throughout the sentence requires measurements of medial sentence positions. Figure 3 (which displays sample velum movement patterns for reiterant sentences) shows that while there was a general decline in the velar peaks over the course of sentences, there were also some local increases and decreases, similar to patterns observed for F_0 and acoustic amplitude. Such local effects have been attributed, at least in part, to stress effects (see Gelfer, 1987).

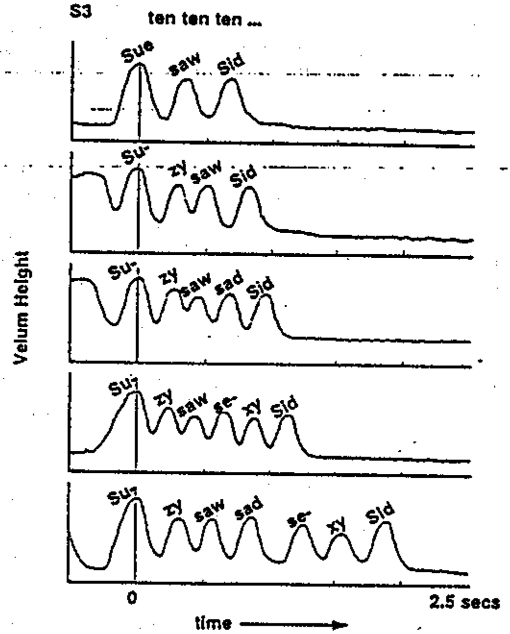

FIGURE 3. Sample velum movement patterns for reiterant sentences at each of five different syllable lengths, produced by Subject 3. The corresponding natural sentences are shown above the traces.

To determine whether there were declination-type effects on medial as well as marginal positions, and to examine the nature of other co-occurring effects, we examined the peaks in the reiterant syllables corresponding to the bisyllabic words, "Suzy," "sexy" and "sassy," in the natural sentences. In this way, it was possible to compare velar peaks for both stressed and unstressed syllables occurring earlier and later in the same sentence. It was, of course, also possible to compare stressed vs. unstressed syllables in the same word.

Note that not all bisyllabic words occurred in all of our sentences. That is, "Suzy" occurred in six of the sentence types, "sexy" in four, and "sassy," in only two (see Table 1). Our first analysis including medial sentence positions examined the effect of stress for each subject's productions of each bisyllabic word. In almost every case, peaks for stressed syllables were higher than peaks for unstressed syllables in the same word (Figure 4). We ran a two-way ANOVA on the effects of stress and sentence length on each of the bisyllables (Table 5).

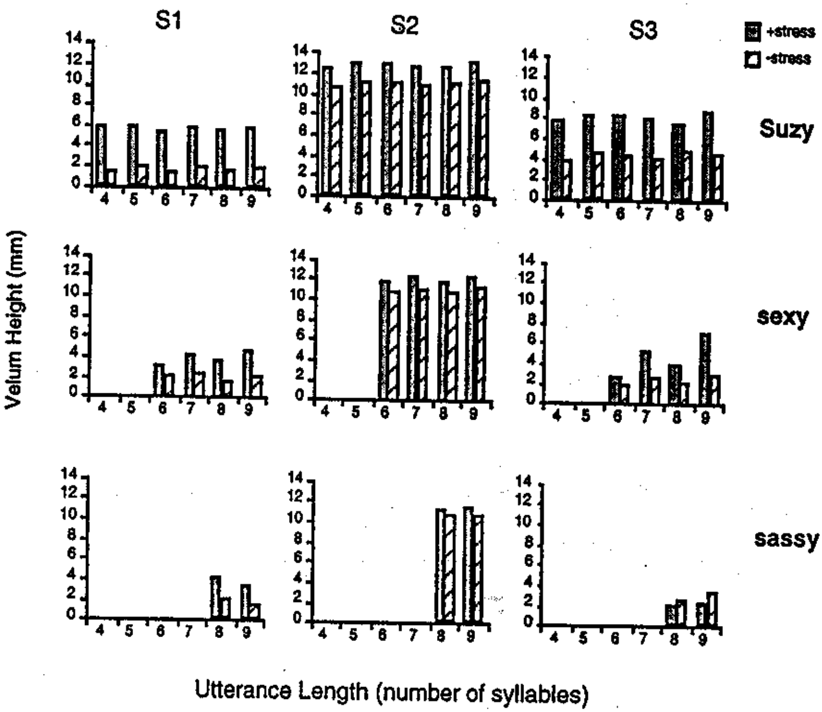

FIGURE 4. Mean values of velar peaks for stressed (dark bars) and unstressed (light bars) syllables in the reiterant versions of the three bisyllabic words, "Suzy" (top), "sexy" (middle), "sassy" (bottom). Data for S1, S2, and S3 are shown at the left, middle, and right, respectively, and are plotted as a function of the number of syllables in the sentences from which the bisyllables were measured.

TABLE 5. *Results of a two-way ANOVA on the effects of stress and sentence length on velar peaks in bisyllabic words.*

Subject:	S1			S2			S3		
SUZY	*F*	(df)	*p*	*F*	(df)	*p*	*F*	(df)	*p*
stress	195.29	1,132	<0.0001	16.16	1,130	<0.0001	91.98	1,132	<0.0001
length	0.38	5,132	NS	0.13	5,130	NS	0.46	5,132	NS
stress × length	0.13	5,132	NS	0.00	5,130	NS	0.42	5,132	NS
SEXY	*F*	(df)	*p*	*F*	(df)	*p*	*F*	(df)	*p*
stress	26.82	1,88	<0.0001	3.57	1,86	NS	38.89	1,88	<0.0001
length	1.36	3,88	NS	0.16	3,86	NS	9.03	3,88	<0.0001
stress × length	0.43	3,88	NS	0.01	3,86	NS	3.31	3,88	<.05
SASSY	*F*	(df)	*p*	*F*	(df)	*p*	*F*	(df)	*p*
stress	12.78	1,44	<.001	0.68	1,42	NS	1.12	1,44	NS
length	1.01	1,44	NS	0.01	1,42	NS	0.59	1,44	NS
stress × length	0.01	1,44	NS	0.03	1,42	NS	0.17	1,44	NS

For the reiterant version of "Suzy," the effect of *stress* was significant for all three subjects, but neither the effect of sentence *length* nor the interaction between the two variables was significant for any subject. That is, stressed syllables consistently had higher peaks than unstressed syllables regardless of sentence length. For "sexy," the effect of *stress* was significant for S1 and S3, and approached significance for S2 ($p = 0.0623$). In all cases, the stressed syllables had the higher peaks. The effect of sentence *length* and the *stress × length* interaction on "sexy" was not significant for S1 or S2. However, both were significant for S3, apparently because the *stress* effect was simply stronger for some sentence lengths than others. For "sassy," there was only one significant effect for any subject, and that was the effect of *stress* for S1, where once again the stressed syllable had a higher peak than the unstressed syllable.

While these analyses examined all stressed and unstressed syllables in bisyllabic words in the study, a separate analysis was undertaken to focus on the two sentences in which all three words occurred (those 8 and 9 syllables in length); they were always in the same order ("Suzy" first, "sexy" next, "sassy" last). This analysis enabled us to determine whether stressed and/or unstressed syllables declined in peak velum height throughout the sentence and whether the difference between stressed and unstressed syllables was affected by sentence position (i.e., earlier vs. later). The data are plotted in Figure 5.

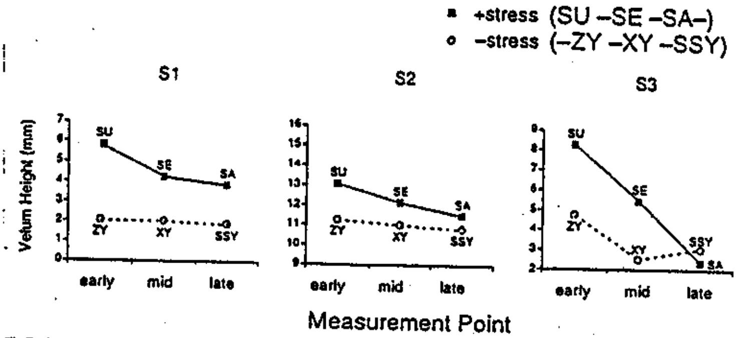

FIGURE 5. Mean values of velar peaks for stressed (filled squares) and unstressed (open circles) syllables in the reiterant speech corresponding to the three bisyllabic words as a function of their relative positions in the sentences ("Suzy" = early; "sexy" = mid; "sassy" = late). Data were obtained from the two longest sentences (8 and 9 syllables in length) as those contained all three bisyllabic words. Data for S1, S2, and S3 are shown at the left, middle, and right, respectively.

We ran two-way ANOVAs on the effects of *word* (first, second, third) and *stress* (stressed/unstressed syllable) on the measures of the reiterant sentences (Table 6). All subjects showed a main effect of *stress*, reflecting the fact that, in all but one case for one speaker, stressed syllables had higher velar peaks than unstressed syllables; the only exception was the reversal of that pattern for S3's last bisyllabic word, in which the unstressed peak was higher than the stressed peak. S1 and S3 also showed significant effects of *word* and significant interactions between *word* and *stress*. The main effect of *word* reflected the fact that overall, earlier words had higher velar peaks than later words; however the interaction and the pattern shown in the graphs meant that stress and word effects had to be untangled.

We examined the effect of *stress* for each of the three words, in an analysis of simple main effects. For S1, the effect of *stress* was significant for 'Suzy,' 'sexy,' and 'sassy' (all $p < 0.01$), although the F value declined across the three words (F = 58.09, 20.18, 15.64, respectively), indicating a reduction in the magnitude of the stress difference over the time course of the sentence.

TABLE 6. *Results of two-way ANOVA on the effects of word position and stress on velar peaks.*

Subject:	S1			S2			S3		
variable	*F*	(df)	*p*	*F*	(df)	*p*	*F*	(df)	*p*
word	5.10	(2,138)	<0.01	1.58	(2,132)	NS	34.47	(2,138)	<0.0001
stress	86.07	(1,138)	<0.0001	6.62	(1,132)	<.05	25.71	(1,138)	<0.0001
word × stress	3.92	(2,138)	<0.05	0.49	(2,132)	NS	12.00	(2,138)	<0.0001

For S3, the effect of *stress* was significant for 'Suzy' and 'sexy' (both $p<.01$), with a reduction in F values ($F = 28.87$, 19.77, respectively), but the effect was not significant for 'sassy,' again consistent with the notion that stress effects are reduced later in a sentence.

Next, we examined the effect of *word* separately for stressed and unstressed syllables. The effect of *word* was significant for stressed ($F = 8.97$, $p < 0.01$), but not unstressed syllables ($F<1.0$, $p = 0.9441$) for S1. The effect of *word* was significant for both stressed and unstressed syllables for S3, with a decline in F values (40.35 and 6.12, respectively) and significance levels ($p < 0.0001$ and $p < 0.01$, respectively). All subjects, including S2, showed a flatter function in the unstressed than stressed syllables, although the difference between stressed and unstressed syllables as a function of position was not significant for S2.

A shortcoming of our study is that *stress* is confounded here with syllable position in a word; stressed syllables were always first syllables and unstressed syllables were always second syllables in these bisyllabic words. Hence, it is unclear whether the effects described are due to stress and/or to within-word declination. However, there are data that indicate that stress probably played an important role. For example, Vaissière (1988) showed that velar peaks for the oral consonants in CVN sequences were higher in stressed than in unstressed syllables—just the pattern that was observed in these data. And, as mentioned in the Introduction, Vayra and Fowler (1992) showed that declination patterns of the jaw and formant frequencies observed in isolated trisyllables are weakened or disappear when the trisyllables are embedded in carrier phrases. Thus, if velar declination is like jaw and formant declination, then there should be relatively little, if any, effect of consonant position in a word when that word is embedded in a sentence (Vayra & Fowler, 1992) assuming, of course, that the consonant occurs in the same syllable position (Krakow, 1993), which is the case here. In light of Vayra and Fowler's study and those of Vaissière and of Krakow, the present data suggest that, in general, velar declination (in the form of increasing relaxation, i.e., decreasing height of velar peaks) is largely restricted to stressed syllables, and that this results in a reduction in the contrast between velar peaks in stressed and unstressed syllables as they occur later in a sentence.

F_0 Data

Figure 6 shows data that we obtained on peak F_0 in the stressed and unstressed syllables of reiterant versions of the three bisyllabic words, "Suzy," "sexy," and "sassy" in the two longest sentences in our study. (These measures correspond to the velar measures presented in Figure 5). The figure shows that F_0 declination occurs in stressed and unstressed syllables, whereas velar declination is limited to stressed syllables. We ran the same statistical analyses on the F_0 data as on the corresponding velar data beginning with a two-way ANOVA on the effects of word (first, second, third) and stress (stressed/unstressed syllable) (Table 7).

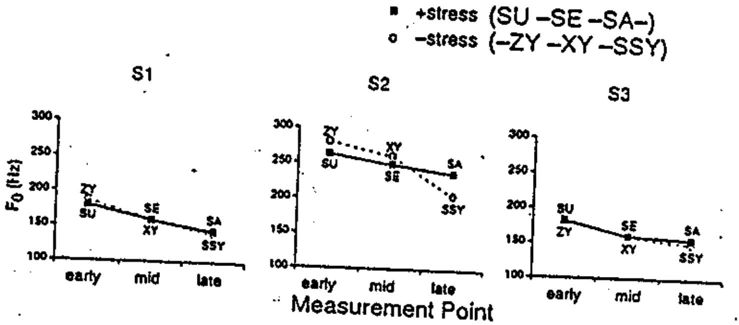

FIGURE 6. Mean values of F_0 peaks for stressed (filled squares) and unstressed (open circles) syllables in the reiterant speech corresponding to the three bisyllabic words as a function of their relative positions in the sentences ("Suzy" = early; "sexy" = mid; "sassy" = late). Data were obtained from the two longest sentences (8 and 9 syllables in length) as those contained all three bisyllabic words. Data for S1, S2, and S3 are shown at the left, middle, and right, respectively.

TABLE 7. *Results of two-way ANOVA on the effects of word position and stress on F_0 peaks.*

Subject:	S1			S2			S3		
variable	*F*	(df)	*p*	*F*	(df)	*p*	*F*	(df)	*p*
word	307.19	(2,138)	<0.0001	25.67	(2,132)	<0.0001	183.30	(2,138)	<0.0001
stress	0.19	(1,138)	NS	0.02	(1,132)	NS	.27	(1,138)	NS
word × stress	6.82	(2,138)	<0.01	7.42	(2,132)	<0.001	1.42	(2,138)	NS

In contrast to the velar data, where the main effect of *stress* was significant for all three subjects, the main effect of *stress* on F_0 peaks was not significant for any of the subjects. In the velar data, only two of the three subjects showed a main effect of *word*; here, all three subjects showed a *word* effect, reflecting the fact that F_0 peaks declined from early to late in the sentences. Two subjects (S1 and S2) showed a *word × stress* interaction on F_0. The nature of this interaction was examined in analyses of simple main effects. For S2, the effect of *word* was weaker (but still significant) in the stressed ($p < 0.05$), than in the unstressed syllables ($p < 0.0001$), the opposite of what was generally observed for the velum; for S1, the effect of *word* was significant for both stressed and unstressed syllables with no difference in the level of significance ($p < 0.0001$). Testing the effect of *stress* for each of the three words for the two subjects who showed an interaction, we observed the following: For S2, *stress* was significant only for "sassy" (where the stressed syllable had a higher F_0 peak than the unstressed syllable; $p < 0.01$); for S1, *stress* was significant for "Suzy" (where the unstressed syllable had a higher F_0 peak than the stressed syllable; $p < 0.01$) and "sassy" (where the stressed syllable had a higher F_0 peak than the unstressed syllable; $p < 0.05$). Overall, then, stress did not appear to play an important or consistent role in declination of fundamental frequency for these data; stressed and unstressed syllables alike showed declination. This result is consistent with what Vayra and Fowler observed for F_0 and acoustic amplitude.

DISCUSSION

We can conclude that declination occurs across the three major physiological systems important in speech—respiratory, laryngeal, and supralaryngeal—based on measures of subglottal pressure, F_0, acoustic amplitude, formant frequencies, and movements of the jaw, lips, and velum. In this study, we observed declination in the velum, thus supplementing the literature on supralaryngeal declination, which previously had been limited to articulators affecting (or acoustic measures reflecting) oral tract shape. We found that peaks of velar elevation for syllable-initial obstruents were consistently lower at the end of a sentence than at the beginning. In addition, the difference between initial and final velar peaks was largest for the longest sentences and smallest for the shortest ones.

Although declination can be described as a general phenomenon in speech, we must conclude that there are differences in the nature of declination as a function of the part of the speech production mechanism involved. Our study, taken with that of Vayra and Fowler (1992), shows a contrast between patterns of the jaw and velum, on the one hand, and F_0 and acoustic amplitude, on the other. That is, the patterns of declination for the supralaryngeal articulators appear more similar to each other than to those of the laryngeal-respiratory systems, which likewise resemble each other. It is important to note, also, that across the studies of declination, causative relations are only evident in the effects of respiration (subglottal pressure) on F_0 and acoustic amplitude (e.g., Gelfer, 1987; Vayra & Fowler, 1992). And while the supralaryngeal measures of jaw, velum and formant frequencies have in common the fact that declination seems largely restricted to stressed syllables, other aspects of the patterns render them dissimilar.

To aid in our discussion of "types" of declination patterns, we have plotted, in Figure 7, data from Vayra and Fowler (1992), (Table 4, p. 55) in a manner parallel to our plots of velar and F_0 data in the sentences with the three bisyllabic words (Figures 5 and 6). Vayra and Fowler's data include F_1, jaw opening, F_0, and acoustic amplitude measures for the vowel /a/ in bVbVbV sequences. Note that while both studies used measures at early, mid, and late positions, Vayra and Fowler's utterances were trisyllabic words, while ours were sentences of eight and nine syllables. In addition, Vayra and Fowler's subjects were Italian speakers while ours were English speakers.

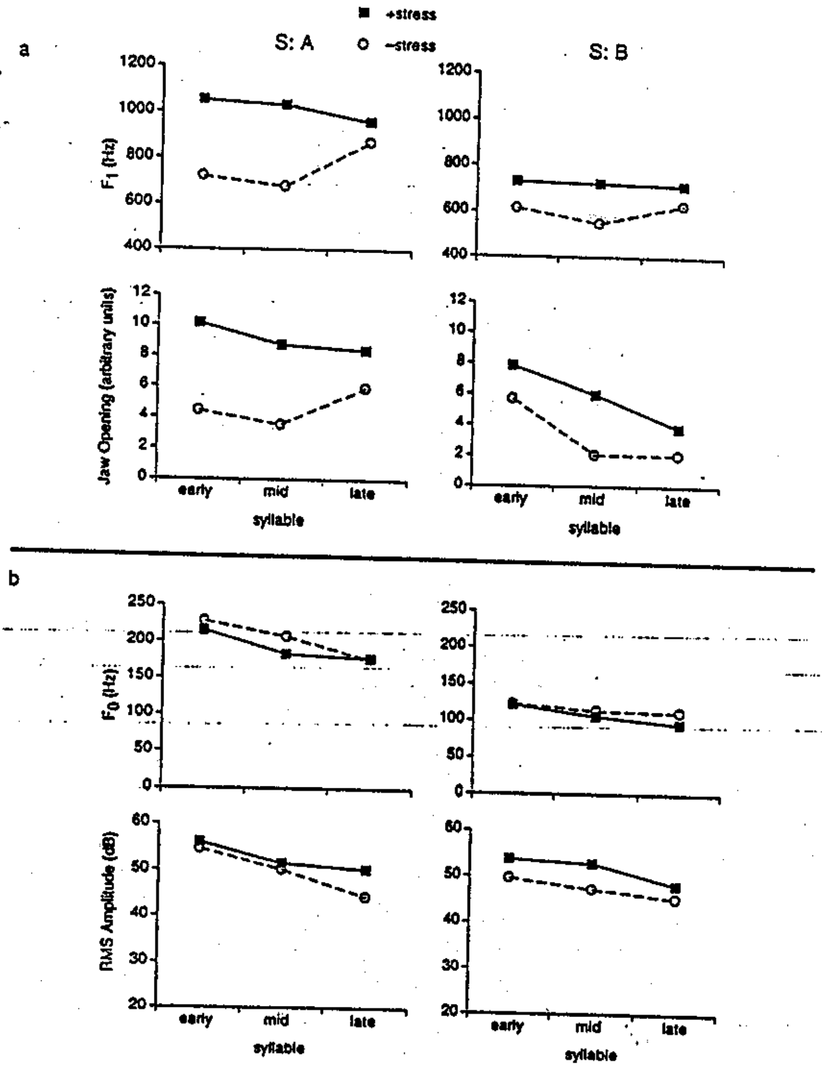

FIGURE 7. Mean values of (a) F_1 and jaw opening and (b) F_0 and acoustic amplitude in stressed (filled squares) and unstressed (open circle) /a/'s in Italian trisyllables, as a function of their relative positions in the sequences (early = vowel 1; mid = vowel 2; late = vowel 3). Data for subject A are at the left, and for B, at the right. (Adapted from Vayra & Fowler, 1992, Table 4, p. 55.)

Figure 7(a) shows their F_1 and jaw opening measures for stressed and unstressed /a/ in each of the three syllables in their trisyllabic words, here labeled 'early,' 'mid,' and 'late.' Consistent with our velar data, Vayra and Fowler reported declination across the three measurement points only for the stressed syllables. Jaw opening decreases and F_1 decreases from early to late, consistent with relaxation of the extreme opening and F_1 measures ordinarily associated with the vowel /a/. In the case of the velar data, increased relaxation was observed in the form of decreasing velar height for the stressed syllables across the three measurement positions. Examination of the F_1 and opening measures in the unstressed syllables show the V-shaped pattern described by the authors, with the smallest jaw opening and the lowest F_1's associated with the middle, rather than the final, syllable. This contrasts with most of the velar data, in which the unstressed syllables showed a rather flat function, with little or no effect of position. However, one of our subjects (3), showed a V-shaped pattern in her unstressed velar peaks, that is, the velar peak for /t/ was lowest in the middle, rather than the final, unstressed measurement position. For both sets of supralaryngeal data, we note that the combined patterns of the stressed and unstressed syllables are such that the contrast between stressed and unstressed syllables is most reduced in the final position.

Figure 7(b) shows Vayra and Fowler's F_0 and acoustic amplitude measures for stressed and unstressed syllables in the three syllables of the test words. Consistent with our F_0 data, these measures show declination effects running from early to late in the sequence, in both stressed and unstressed syllables, with lower F_0's and reduced amplitude at each successive measurement point. The results for the respiratory-laryngeal measures, then, are highly similar across the two studies, whether obtained in isolated trisyllables or in sentences, supporting Vayra and Fowler's notion that isolated trisyllables take on sentence intonation. And, as noted in both studies, the supralaryngeal measures differ from the F_0 and/or acoustic amplitude measures, in that the former show continuous declination effects only for stressed syllables. The lack of a parallel pattern for velar and F_0 data supports Vayra and Fowler's (1992) contention, based on the difference in their jaw opening and F_1 data vs. F_0 and acoustic amplitude data, that supralaryngeal declination cannot be said to be the result of respiratory declination in the way that the decline in F_0 and acoustic amplitude is a result of subglottal pressure declination. As noted by Fowler (1988), the exclusive focus of earlier declination studies on F_0 was misguided not only because the effects are more general, but because F_0 effects in particular are largely the result of declining subglottal pressure.

In summary, our findings of velar declination expand the investigations of supralaryngeal declination begun by Fowler and her colleagues that included a variety of measures of the jaw, lips, and formant frequencies (Fowler, 1988; Vatikiotis-Bateson & Fowler, 1988; Vayra & Fowler, 1992). Our findings also add to a growing body of literature that highlights the importance of velar movement patterns at different levels of speech organization, from the segmental to the syllabic and prosodic (for reviews, see Bell-Berti, 1993; Krakow, 1993). Previously reported prosodic effects on the velum include those of stress (Vaissière, 1988; Krakow, 1993) and speaking rate (e.g., Bell-Berti & Krakow, 1991; Kuehn, 1976), and the present work highlights an interaction between position in a sentence and stress. An interaction between these two variables, it is suggested here, may turn out to be a hallmark of supralaryngeal declination. How other non-segmental variables, such as speaking rate and position in a syllable interact with velar declination, or, indeed, how different segment types affect the pattern, have yet to be investigated.

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REFERENCES

Bell-Berti, F. (1993). Understanding velic motor control: Studies of segmental context. In M. K. Huffman & R. A. Krakow (Eds.), *Nasals, nasalization, and the velum. (Phonetics & Phonology V)* New York: Academic Press, 63-86.

Bell-Berti, F., & Krakow, R. (1991). Anticipatory velum lowering: A coproduction account. *Journal of the Acoustical Society of America, 90,* 112-123.

Breckenridge, J. (1977). Declination as a phonological process. (Bell System Manuscripts, Murray Hill, NJ)

Cohen, A., Collier, R., & 't Hart, J. (1982). Declination: Construct or intrinsic feature of pitch? *Phonetica, 39,* 254-273.

Cooper, W., & Sorenson, J. (1981). *Fundamental frequency in sentence production.* New York: Springer Verlag.

Fowler, C. (1988). Periodic dwindling of acoustic and articulatory variables in speech production. *Paw Review, 3,* 10-13.

Gelfer, C. (1987). *A simultaneous physiological and acoustic study of fundamental frequency declination.* Unpublished doctoral dissertation. New York: City University of New York.

Horiguchi, S., & Bell-Berti, F. (1987). The Velotrace: A device for monitoring velar position. *Cleft Palate Journal, 24,* 104-111.

Kay, B. A., Munhall, K. G., Vatikiotis-Bateson, E. V. , & Kelso, J. A. S. (1985). A note on processing kinematic data: Sampling, filtering, and differentiation. *Haskins Laboratories Status Reports on Speech Research, SR 81*, 291-303.

Kent, R. D., Carney, P. J., & Severeid, L. R. (1974). Velar movement and timing: Evaluation of a model for binary control. *Journal of Speech and Hearing Research, 17*, 470-488.

Krakow, R. A. (1989). *The articulatory organization of syllables: A kinematic analysis of labial and velar gestures*. Unpublished doctoral dissertation, Yale University.

Krakow, R. A. (1993). Nonsegmental influences on velum movement patterns: Syllables, sentences, stress, and speaking rate. In Huffman, M. K. & Krakow, R. A., (Eds.) *Nasals, nasalization, and the velum*. (*Phonetics & Phonology V*) New York: Academic Press, 87-118.

Kuehn, D. P. (1976). A cineradiographic investigation of velar movement in two normals. *Cleft Palate Journal, 13*, 88-103.

Lieberman, P. (1967). *Intonation, perception and language*. Research Monograph No. 38. Cambridge: MIT Press.

Liberman, M., & Streeter, L. A. (1978). Use of nonsense-syllable mimicry in the study of prosodic phenomena. *Journal of the Acoustical Society of America, 63*, 231-233.

Pierrehumbert, J. (1979). The perception of fundamental frequency declination. *Journal of the Acoustical Society of America, 66*, 363-369.

't Hart, J., Collier, R., & Cohen, A. (1990). *A perceptual study of intonation: An experimental-phonetic approach to speech melody*. Cambridge, New York: Cambridge University Press.

Vaissière, J. (1988). Prediction of articulatory movement of the velum from phonetic input. *Phonetica, 45*, 122-139.

Vatikiotis-Bateson, E., & Fowler, C. (1988). Kinematic analysis of articulatory declination. *Journal of the Acoustical Society of America, 84*, S128 (A).

Vayra, M., & Fowler, C. A. (1992). Declination of supralaryngeal gestures in spoken Italian. *Phonetica, 49*, 48-60.