KINEMATIC ANALYSIS OF VOWEL PRODUCTION IN GERMAN

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One major typo corrected: Fig. 2 was erroneously referred to as Fig.4

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ABSTRACT

The tense and lax vowels of German were compared, based on an analysis of the duration, amplitude and velocity characteristics of lip and tongue movement. This study examined firstly whether they show different patterns of compression over changes in speech rate, and secondly whether velocity profiles would reveal evidence of different underlying control mechanisms. CVC movements were segmented into CV, nucleus and VC portions. Speech rate affected duration of CV and VC movements similarly for tense and lax vowels. However, the effect on nucleus duration was vastly greater for the tense vowels. Analysis of the velocity profiles of CV and VC movements in terms of the ratio of peak to average velocity showed no differences between tense and lax vowels, once differences in duration were taken into account. The conclusion is that tense and lax vowels share similar control mechanisms for the elementary CV and VC movements, but differ radically in the way these elements are concatenated.

1. INTRODUCTION

The overall aim of this work is a better understanding of the relationship between phonological and articulatory dimensions in vowel production. For this, consideration of a complex vowel system such as that found in German should be particularly revealing; for example, the German system includes contrasts on the tense-lax dimension, the rounded-unrounded dimension, and combinations thereof. This paper will be concerned with the dynamic characteristics of vowel articulation. As recently pointed out by Johnson [1], work on human vowel perception has made clear the importance of dynamic information, yet there are very few studies of the underlying articulatory relationships. For German this is particularly unfortunate since the tense-lax contrast, on which we will be focussing, also involves restrictions in syllable structure, with lax vowels only occurring in closed syllables. It may thus be hypothesized that better insight into vowel production can only be achieved by examination of the temporo-spatial structure of complete syllables.

Indeed, there is a long tradition in the phonology of German of viewing the tense-lax distinction as a difference in the link between vowel and following consonant (recently [2]). However, attempts (mostly on the basis of acoustic analysis) to provide a phonetic foundation for these approaches have been inconclusive (e.g [3]). It seemed plausible that detailed articulatory data might shed new light on this old problem.

The specific aim of this paper will thus be to determine whether tense and lax vowels are characterized by different movement patterns. But of course we have to take into account that these two vowel classes differ also in length. In order to identify kinematic patterns that are truly characteristic of vowel class, and not just a simple spin-off of length differences we need to introduce a further independent source of durational variation. Here we use a speech-rate contrast. In fact, the relationship between speech-rate and the tense-lax distinction is a particularly interesting one, since there are indications from the literature that the two vowel classes show different patterns of compression as a function of speech rate (e.g. [4], cf. also [5]), lax vowels being more resistant to compression. Although these investigations serve to reinforce the introductory assertion that closer consideration of the dynamic aspects of vowel production is warranted, they leave open the question as to what the precise articulatory substrate of differential patterns of compression might be.

2.MATERIAL AND PROCEDURE

Five German speakers spoke 5 repetitions of a nonsense-word corpus of the form /gəCVCə/ with C1=C2=/p, t, k/ and with V consisting of the following 7 pairs of tense-lax vowels: **/ iː ɪ, yː ʏ, eː ɛ, øː œ, ɑː a, oː ɔ, uː ʊ /**. The test words were embedded in a carrier phrase. The corpus was recorded at two speech rates: "Normal" in the first session, "Fast" in the second. The faster rate was so chosen that the duration of the tense vowels at the fast rate should approach that of the lax vowels at the normal rate. Rate was controlled by regular presentation of taped example utterances.

Electromagnetic articulography (AG100, Carstens Medizinelektronik) was used to monitor movement of tongue (4 transducer coils mounted approx. 1 to 6 cm from the tongue tip), lower lip and jaw. Reference coils on upper incisors and bridge of nose were used to compensate for head movement.

Articulatory analysis was based on the movement of the coil assumed to be most intimately connected with articulatory closure for the respective consonantal context, i.e lower lip for /p/, frontmost tongue coil for /t/, rearmost tongue coil for /k/.

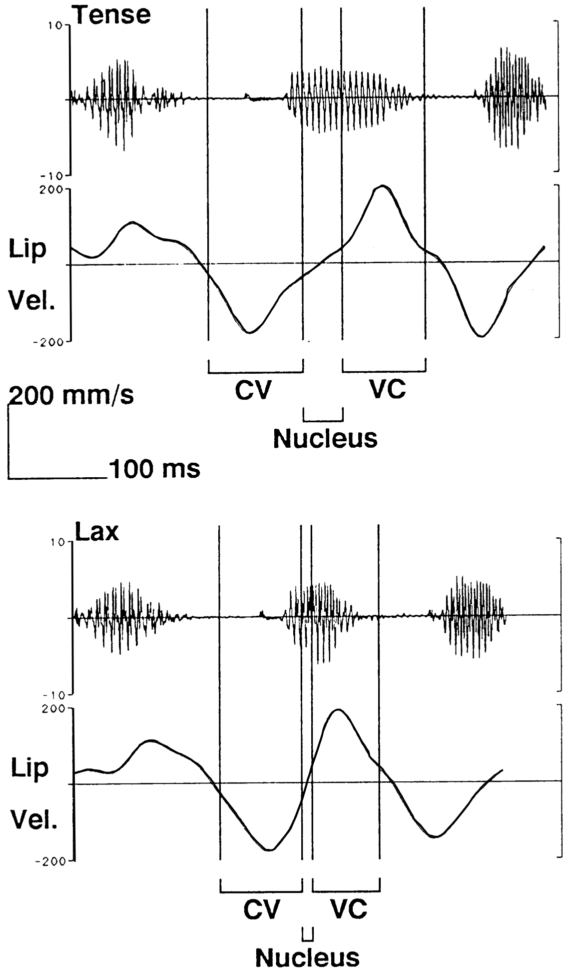


*Fig. 1: Example of the segmentation procedure for an utterance with tense vowel (/ **p iː p** /, top) and lax vowel (/ **p ɪ p** /, bottom). For illustrative purposes the speed of lower-lip vertical movement is shown. In practice, the tangential velocity curve was used.*

Each CVC movement was analyzed in terms of the following three segments: CV, nucleus, and VC. These are illustrated in Fig. 1 and defined as follows: CV onset and offset are the points where overall velocity rose above (onset) and fell below (offset) 20% of the maximum velocity in the movement from C1 target to vowel target. The VC segment was defined analogously for the movement from vowel to C2. The nucleus corresponds to the portion between CV offset and VC onset. The CV and VC segments were constrained to include only one relative velocity maximum. This constraint, as well as the use of the rather high threshold value of 20% were motivated by the desire to avoid possible problems with poorly defined transitions into or away from a quasi-steadystate phase (for tense vowels at the normal rate the nucleus could be substantially longer than in the example in Fig. 1). This also provided part of the motivation for defining a nucleus, rather than choosing a single point to separate CV and VC segments. The use of the nucleus was also motivated by a difference that we frequently observed in the acceleration patterns of tense and lax vowels. Nucleus duration can be regarded as a measure of relative acceleration at the point of zero or minimum velocity separating CV and VC segments. In the lax example of Fig.1 acceleration at this point is close to maximum. For the tense vowels it is relatively low. One reason for this is that for the tense vowels the peak deceleration of the opening CV movement, and the peak acceleration of the closing CV movement (both these peaks having the same sign) are separated in time, whereas for the lax vowels they merge into a single peak.

3. RESULTS

Preliminary analysis of vowel duration from the speech wave for the two speech rates showed that the lax vowels compressed less than the tense vowels: about a third as much in absolute terms, and about half as much in percentage terms. Below, we look in detail firstly at the durations of the three kinematically defined segments, and secondly at the relationship between duration, displacement and peak velocity of the CV and VC segments.

3.1 Analysis of kinematically defined durations

First of all, median durations were computed over the 5 repetitions of each item in order to facilitate pair-wise comparison of the tense-lax and speech-rate effects for each subject, vowel and consonant context. The following analyses are thus based on a maximum of 105 values (5 subjects * 3 consonants * 7 vowel pairs) for each combination of tenseness and speech rate.

The three parts of Table 1 show the average results for the four experimental conditions given by the combinations of two vowel categories (rows) by two speech rates (columns) for the CV, nucleus and VC segments. The table gives the durations for each condition, together with the absolute (in ms.) and relative (in %) differences between conditions (row-wise and column-wise). The bottom row and rightmost column of the tables indicate the consistency of the differences, expressed as the percentage of individual pairwise comparisons showing a difference in the same direction as the averaged result.

The most striking result revolves around the behaviour for the nucleus on the one hand, compared with the CV and VC segments on the other hand. For the CV and VC segments the tense vowels contract slightly more than the lax vowels in both absolute and percentage terms going from the normal to the fast speech rate. Accordingly the lax vowel duration is closer in percentage terms to tense vowel duration at the faster rate. However, these differences in the behaviour of the two vowel categories are rather slight compared with the differences found for the nucleus. For the lax category the contraction of the nucleus from the normal to the fast rate amounts to 12.5%, which is almost exactly the same percentage change as is found for the CV and VC segments - though given the shortness of the nucleus for the lax vowels the change in absolute terms is negligible: less than 2 ms. For the tense vowels, however, the nucleus shows a massive contraction of 52.3% from the normal to fast rate. Thus although the nucleus is the shortest of the three segments for the tense vowels, it makes easily the largest contribution in absolute terms (29.2 ms) to the overall compression of these vowels.

CV SEGMENT

	Norm.	Fast	Normal-Fast Diff. Abs.	Rel. %	Cons. %
Tense	100.6	81.3	19.3	19.2	91
Lax	77.9	67.0	10.9	14.0	86
Tense-Lax Diff.					
Abs.	22.7	14.3			
Rel. (%)	22.6	17.6			
Cons. (%)	90	82			

VC SEGMENT

	Norm.	Fast	Normal-Fast Diff. Abs.	Rel. %	Cons. %
Tense	76.4	62.4	14.0	18.3	88
Lax	60.5	53.5	7.0	11.6	83
Tense-Lax Diff.					
Abs.	15.9	8.9			
Rel. (%)	20.8	14.3			
Cons. (%)	94	83			

NUCLEUS SEGMENT

	Norm.	Fast	Normal-Fast Diff. Abs.	Rel. %	Cons. %
Tense	55.8	26.6	29.2	52.3	95
Lax	14.8	12.9	1.9	12.5	77
Tense-Lax Diff.					
Abs.	41.0	13.7			
Rel. (%)	73.5	51.5			
Cons. (%)	100	92			

Table 1: Average durations for tenseness and speech-rate conditions; absolute and relative differences between conditions; consistency of differences. All figures in ms unless indicated otherwise (%). From top to bottom: CV, VC and Nucleus segments.

One further difference between the nucleus durations for tense and lax vowels that is not apparent from Table 1 is that for the tense vowels the duration is much more variable not only between speech rates, but also within each speech rate. For the lax vowels the s.d. is 3.6 and 2.9 ms at the normal and fast rates respectively, so the duration remains rather constant over vowels, consonant contexts and speakers. For the tense vowels the respective s.ds are 24.3 and 16.9 ms. For the fast rate this implies that tense nucleus duration did occasionally reduce to the range found for the lax vowels.

Given the constraint that lax vowels must occur in closed syllables one question that arises is whether lax vowels may behave differently from tense vowels particularly with respect to the VC phase (cf. Introduction). In terms of the durational measurements given in the present section this could, for example, mean that the ratio of lax duration to tense duration is different for the VC and CV segments. However, as Table 1 shows, no clear effects of this nature are to be seen.

3.3 Velocity profiles of CV and VC segments

The aim of this section is to determine whether tense and lax vowels show differences in their velocity profiles, in particular those that remain after differences in duration and displacement have been taken into account.

In common with almost every other study of speech movment a very close relationship between peak velocity and displacement was observed. In addition, the slope of this relationship, corresponding to the stiffness term in the mass-spring model of movement, was higher for conditions with shorter durations, i.e for lax vs. tense vowels (cf. [1] for American English) and fast vs. normal rate.

Ostry & Munhall [6] showed that the relationship between stiffness and duration can be well captured by an equation of the form:

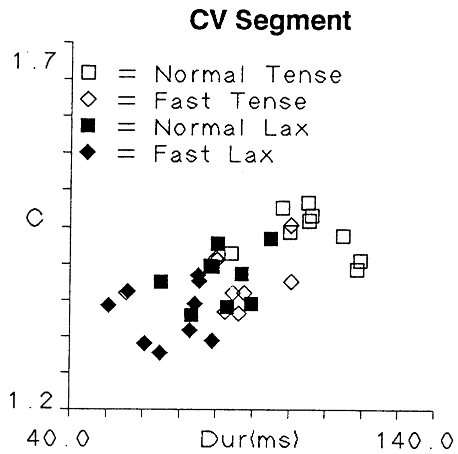
(1) peak velocity/displacement=**c**/duration

In our data there was indeed a very close relation between stiffness and the reciprocal of duration. Correlation coefficients were over 0.9 both when all data (i.e all CV or all VC movements) for the individual subjects were analyzed (n=ca. 400), as well as when data for all subjects were pooled (n=ca.2000).

The empirically determined parameter **c**, derivable for each individual movement by rearrangement of the above equation is equivalent to the ratio of peak velocity to average velocity, and can thus be used to capture the shape of the velocity profile, allowing assessment of the geometrical similarity of movements differing in displacment and duration (see [7] for other measures of velocity profile similarity). Specific values of this shape coefficient can be related to potential underlying control principles, e.g minimum jerk [6]; however, we will not be following this line of enquiry here, but will simply be using **c** as a convenient means of assessing the kinematic similarity of tense and lax vowels over the rate manipulations. (Note also that the values of **c** reported here are biased to lower values by our use of the 20% velocity threshold for movement onset and offset.)

Although the high correlations between stiffness and duration just noted indicate that a single value of **c** would generate a function that fits all the data very well, there still remains the possibility of small but systematic differences in the shape coefficient for the different experimental conditions.

It turns out first of all that **c** itself varies slightly with duration (see [7,8] for similar findings). Accordingly, when looking for an influence of the experimental conditions on the shape coefficient, it is necessary to take duration into account. Figure 2 plots this parameter as a function of duration; one panel each for CV and VC movements. Each data point plots the average value for one subject for one experimental condition of tenseness, speech rate and consonantal context. (Data points for the /k/ context have been omitted as they showed a lot of unsystematic variability. This was almost certainly due to analysis difficulties caused by a frequent absence in this context of unambiguous velocity minima corresponding to vowel or consonant targets.)



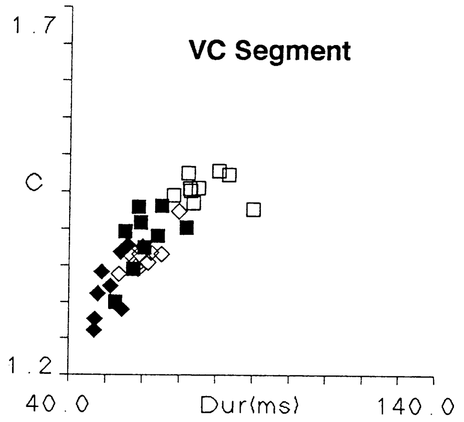


Fig. 2: Shape coefficient ***c*** *of velocity profile plotted as a function of duration. Top: CV movements; Bottom: VC movements. Normal rate: Squares; Fast rate: Diamonds. Tense: Empty symbols; Lax: Filled symbols.*

The first point to note from Fig. 2 is that while both CV and VC movements show a tendency for **c** to increase with duration, the relationship is sharper, and the slope is steeper for VC movements. Because of this steeper slope, longer duration VC movements also have higher **c** values than CV movements with comparable durations. While there are thus consistent differences between VC and CV movements, there do not seem to be any differences in characteristic values of **c** for tense and lax vowels once durational differences are taken into consideration.

4. CONCLUSIONS

The results provided improved insight into the organisational principles underlying articulator movement in tense and lax vowels. It is important to note that without the incorporation of the speech-rate condition unambiguous interpretation would have been considerably hampered. The crucial durational difference between tense and lax vowels involved the nucleus segment. It should be emphasized that we do not see this segment as a kind of steady-state phase. Rather, the duration and the variability in the duration of the nucleus can more profitably be seen as a measure of the tightness of the coupling between the CV and VC movements: tight for lax vowels, loose for tense vowels. In contrast to this difference in the serial organisation of movement, the two vowel classes did not show any obvious differences in the internal organisation of the individual movement elements themselves, i.e. the CV and VC segments, as judged by analysis of the velocity profiles. The results thus gave answers to these linguistically oriented questions. On the other hand, the fact that vocal tract opening (CV) and closing (VC) movements showed slight differences in velocity profile, or at least a different dependency on duration, will require further examination from a more general motor control perspective.

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