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TENSE AND LAX VOWELS - DEGREE OF CONSTRICTION OR PHARYNGEAL VOLUME?

Sidney Wood
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Introduction

There are differences of both the degree of tongue constriction and the volume of the lower pharynx between tense and lax vowels. These factors are modifications of the configuration of the vocal tract and will consequently alter its resonances. For a complete account of the production of different vowel categories, it is necessary to know the magnitude of acoustical difference that can be referred to any particular articulatory variable. The nomograms published by Stevens and House (1955) and Fant (1960) based on the three-parameter model have been very helpful in describing the acoustical properties of the vocal tract but their usefulness is strictly limited by the difficulty of relating the model parameters to specific articulatory manoeuvres in a number of situations. The exploration of the acoustical consequences of lip, tongue, jaw and larynx movement by Lindblom and Sundberg (1971) has shown the way to the solution of this type of problem. A midsaggital profile of the vocal tract is deliberately altered and the resonances of each configuration are measured or calculated. This can be done either by computer or with the aid of an electrical analogue. The experiments to be described below were designed to assess how much of the acoustical difference within pairs of tense and lax vowels can be attributed to the degree of constriction and how much to the pharyngeal volume. Midsaggital profiles of the vocal tract were systematically modified, the corresponding area functions set on an electrical vocal tract analogue (LEA[1]) and the resonance frequencies found and measured.

Tense and lax vowels

The terms tense and lax are notoriously ambiguous in both phonetics and phonology. There are two types of ambiguity I particularly wish to underline. The one concerns the physiological and acoustical character of the contrasts. This ambiguity is not so serious since it reflects our limited knowledge of the production processes involved. As our knowledge improves, this amgiguity will be resolved. Far more serious is the confusion of tenseness and laxness with vowel length or quantity.

I shall restrict the terms tense and lax exclusively to the timbre differences in such pairs as [i-ɪ, e-ɛ, u-ʊ, o-ɔ, ɑ-a] (and the rounded palatals [y-ʏ, ø-œ] which for the remainder of this report will be subsumed with the spread-lip palatals). This usage is not inconsistant with the traditional definition in terms of muscular tension of the tongue which implies differences of lingual articulation and consequently of vocal tract configuration and resonance. There is necessarily an acoustical difference between tense and lax vowels.

There is a well known tendency for tense vowels to be longer than lax vowels. This is usually said to be due to the tense gestures taking more time to execute. It is an undeniable fact that in many languages tense vowels are long and lax vowels short. But other relationships are also found such as timbre contrasts between vowels of the same length or quantity contrasts between vowels of the same timbre. The relationship between tenseness and quantity can vary synchronically from language to language and diachronically from period to period in one and the same language. The relationship between tense vowels, long vowels and diphthongs is complex and does not become simpler if *tenseness* and *quantity* are treated as equivalent. The examples at Table 1 follow from distinguishing between *tense-lax* timbre contrasts and *long-short* quantity contrasts.

	TENSE					LAX				
LONG	i:	e:	u:	o:	ɑ:		ɛ:		ɔ:	a:
SHORT	i	e	u		ɑ	ɪ	ɛ	ʊ	ɔ	a

Table 1. Tense-lax and long-short pairs of vowels. The contrast /i:-i/ is *long* versus *short* (tense). A contrast /i:-ɪ/ is *long and tense* versus *short and lax*. A contrast /i-ɪ/ is *tense* versus *lax*.

Vocal tract differences

Tracings of X-rayed vowel articulations reveal consistent differences of both degree of constriction and of pharyngeal volume between tense and lax vowels. In addition, there are also differences of lip position (less rounded, sometimes less spread, for lax vowels) and larynx position (deeper for tense vowels, especially for rounded vowels). The articulatory gestures involved appear to be much the same irrespective of language, which points to a universal physiological and biological basis for the acoustical contrasts founded on this difference. I have drawn this conclusion from analysis of the same collection of published sets of X-ray tracings as was used for my criticism of the tongue-arching model (1975). As a control on these conclusions, I have also analysed five X-ray motion films (English, Egyptian, Southern Swedish and West Greenlandic Eskimo) that have been made in Lund[2]. The following is a summary of the findings that are relevant to the present problem[3].

The degree of constriction is quantified as the cross-section area of the vocal tract at the tongue constriction.

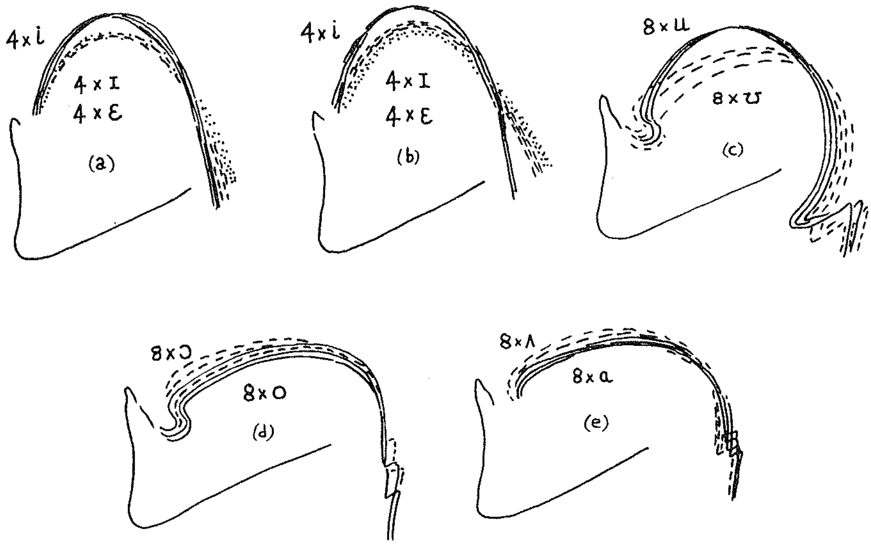


Fig. 1. Sets of tongue profiles for tense-lax pairs by a Southern British English subject. There are 8 examples of each vowel, 4 uttered a little slower than average everyday speech (4.5 syllables/sec) and 4 a little faster (6.5 syllables/sec). The main articulatory consequence of the rate difference was a narrower jaw-opening for open vowels [ɛ , o, ɔ, ɑ, ʌ]. There was hardly any influence on the tongue profile, except for the palatal [ɛ] where the tongue was lower relative to the mandible in the faster set (b) to compensate for the higher position.

There is considerable similarity of constriction size for similar vowel qualities irrespective of language. Typical ranges are given in Table 2.

CONSTRICTION	HARD PALATE		SOFT PALATE	UPPER PHARYNX	LOWER PHARYNX	
VOWEL PAIR	i/ɪ	e/ɛ	u/ʊ	o/ɔ	ɑ/a	
TENSE VOWEL	0.5-1.0	1.0-1.7	0.5-1.0	0.6-1.0	0.5-1.0	cm^2
LAX VOWEL	1.6-2.2	2.5-3.0	1.5-	0.4-0.7	1.3-1.7	

Table 2. Cross-section area of the vocal tract at the tongue constriction, representing the degree of constriction. The tense vowel has the narrower constriction, except for the [o-ɔ] pair.

Each pair is characterized by a widening of the constricted passage by 3-4 mm for the lax vowel. The exception is the [o-ɔ] pair where the lax vowel just has the narrower con-

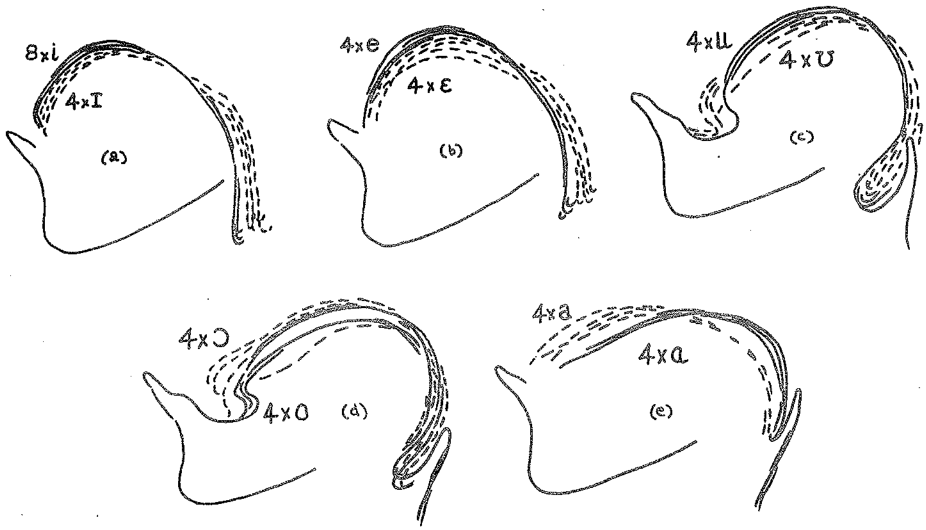


Fig. 2. Sets of tongue profiles for tense-lax pairs by an Egyptian subject. There are four examples of each vowel, except for [i]. The [a] quality represents /a/ in a "non-emphatic" environment while [ɑ] represents 2 x /a/ and 2 x /a+a/ in an "emphatic" environment.

striction although both ranges virtually overlap. In the case of [ʊ], when the velar passage is widened beyond 2.0 cm^2 the back of the tongue begins to constrict the upper pharynx instead. The quoted ranges are characteristic for each vowel quality.

For all these pairs (except [ɑ-a]), there are corresponding differences in the lower pharynx (Table 3). In the case of the [ɑ-a]-like vowels, the lower pharynx is constricted by the tongue so that variation of low pharyngeal width therefore modifies the constriction itself. Moreover, the tense vowel [ɑ] has the narrower pharynx.

Physiologically, these differences of degree of constriction and low pharyngeal volume are created by the movement of the tongue. This movement must be broken into its lingual and mandibular components (Lindblom and Sundberg, 1971). The tongue constriction is formed by directing the tongue

CONSTRICTION	HARD PALATE		SOFT PALATE	UPPER PHARYNX	
VOWEL PAIR	i/ɪ	e/ɛ	u/ʊ	o/ɔ	
TENSE VOWEL	25-30	19-23	25-30	15-22	mm
LAX VOWEL	19-23	16-20	19-23	11-19	

Table 3. Typical ranges of low pharyngeal width from the tongue to the rear pharyngeal wall at the epiglottis. The absolute measure depends on the size of the subject's valleculae and is highly variable between individuals. The tense vowel always has the wider lower pharynx.

itself towards (i) the hard palate (for palatal [i-ɪ, e-ɛ]-like vowels), (ii) the soft palate (for palatovelar [u-ʊ]-like vowels), (iii) the upper pharynx (for pharyngovelar [o-ɔ]-like vowels) and (iv) the lower pharynx (for low pharyngeal [ɑ-a]-like vowels) as can be seen at Figs. 1 and 2. At the same time the tongue is raised or lowered bodily by the jaw. This contributes to the constrictions made against the roof of the mouth, i.e. for the palatal and palatovelar vowels. Constrictions in the pharynx are hardly affected by mandibular movement. The jaw occupies two relevant positions during vowels - a closer opening of 5-10 mm for [i, ɪ , u, ʊ]-like vowels and a wider opening of 11-16 mm or more for [e, ɛ , o, ɔ, ɑ, a]-like vowels. The variation depends on such factors as articulation rate and speaking effort. The tongue compensates for the freedom of jaw movement in order to maintain a suitable palatal or palatovelar constriction size (mandibular movement is in the direction of the constriction in these cases). Such lingual compensation is not necessary for the pharyngeal constrictions (but the lips compensate for variation of jaw position in all rounded vowels).

It has been reported that the tongue root is further forward for tense than for lax vowels. The proposed feature advanced tongue root was based on this observation (Halle and Stevens 1969, Perkell 1971). One consequence of advancing the tongue root is to widen the lower pharynx and thus increase its volume. A second consequence is to raise the tongue body, which is in the direction of the constriction in the case of the palatal and palatovelar vowels. The muscles that would pull the tongue root forward are the posterior fibres of the genioglossi. These fibres are also said to assist in raising the tongue. This manoeuvre is necessary for all vowels with a constriction against the roof of the mouth ([i, ɪ, e, ɛ, u, ʊ]). Figs. 1 and 2 show how the tongue root is drawn forward for all these vowels and also how differences of tongue root position between tense and lax vowels in this group are correlated with the height of the tongue relative to the mandible. For the vowels with constricted pharynx ([o, ɔ, ɑ, a]) contraction of the posterior fibres of the genioglossi would be contrary to the rearward constriction-forming gestures. In the case of the pharyngovelar [o, ɔ]-like vowels, it is nevertheless theoretically possible to vary the tongue root position below the upper pharyngeal constriction. Figs. 1 and 2 suggest there was little difference of tongue root position between [o] and [ɔ] for these two subjects, but the tendency was for the tongue root to be more advanced for [o]. In the case of the low pharyngeal [ɑ, a]-like vowels, advancing the tongue root would immediately widen the constriction towards the lax vowel and cannot therefore be utilized for the tense vowel. Figs. 1 and 2 show that for this pair the tongue root is advanced to widen the low pharyngeal constriction for the lax vowel.

The role of the degree of constriction

Sweet (1906) noted that the passage above the tongue appeared to be narrower for tense vowels, the tongue being more "convex". This represents a modification of tongue height (i.e. the sum of the vertical lingual and mandibular

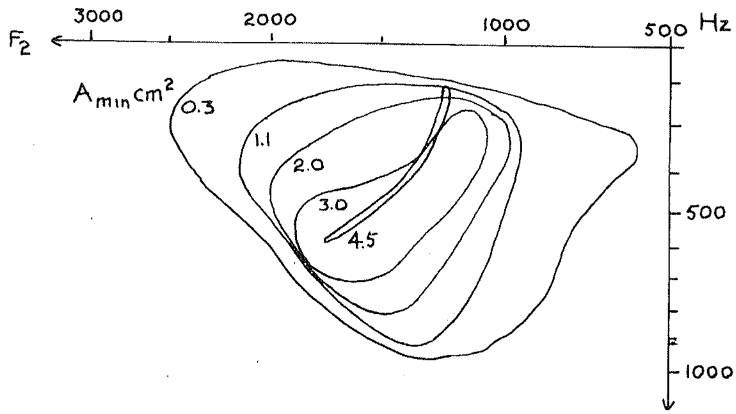


Fig. 3. The maximum possible spectral ranges for F1 and F2 at different degrees of constriction (A_{min} cm^2). This is based on the Stevens and House (1955) three-parameter model nomograms. Each ring encloses the spectra generated by all combinations of constriction location and mouth-opening size for the stated constriction size.

gestures). Tongue height modifies the tongue constriction only in the case of the [i, ɪ, e, ɛ] -like vowels (constricted hard palate) and the [u, ʊ] -like vowels (constricted soft palate). For the vowels with constricted pharynx, the degree of constriction is hardly related to tongue height. In the case of the vowels with constricted lower pharynx, the constriction is indeed narrower for [ɑ] and wider for [a]. This is not exactly what Sweet had had in mind, however, although it is a natural extension of his original idea. He admitted that his distinction between narrow and wide vowels was "not clear in the back vowels where the convexity of the tongue seems to be accompanied by tension of the uvula and soft palate". Sweet was on the track of the truth, that the degree of constriction is a relevant resonator variable in the vocal tract and that differences in the degree of constriction are associated with tenseness and laxness. But his preference for the tongue-arching model, coupled with the impossibility of observing internal articulations and configurations before the discovery of X-rays, effectively concealed the solution from him.

What is the effect of varying the degree of constriction?

The vocal tract is divided into two cavities, one above and one below the tongue constriction. The degree of constriction determines the amount of coupling between the two cavities - that is, the extent to which they resonate together or independently of each other. At the one extreme, the constriction is so narrow that the two cavities influence each other relatively little. At the other extreme, the constriction is so wide that the tract becomes a single uninterrupted pipe. Some idea of the consequence of varying the degree of constriction between these extremes is illustrated by Fig. 3 which is based on the Stevens and House nomograms. The degree of constriction is represented by the cross-section area at the constriction, A_{min} cm^2. Each ring encloses an area representing the frequencies of the first and second formants generated by all combinations of constriction location and mouth-opening size for the stated degree of constriction. A constriction of 0.3 cm^2 is about the narrowest possible for pure vowel sounds, further narrowing leading to the production of turbulence in the constriction. At a constriction of 4.5 cm^2, the vocal tract approaches the uniform tube configuration so that the constriction location no longer exerts any influence. Fig. 3 suggests that the possible spectral range is dependent on the degree of constriction. For the maximum possible spectral range, the very small constriction size would be necessary. As the constricted opening widens, the possible spectral range would be reduced. This would mean that the vocal tract resonances are very sensitive to the degree of constriction, as has also been suggested by Gunnilstam (1974). A few millimetres of tongue movement at the constriction would cause a considerable spectral difference. Unfortunately, we cannot be certain that this is due to the degree of constriction alone, since modification of the degree of constriction in the three-parameter model simultaneously involves a change of the low pharyngeal volume.

The role of the lower pharynx

In Sweet's day, the existence of more than one vocal tract resonance was a highly controversial subject among most phoneticians and interest was limited to the bucchal cavity and the crown of the tongue arch. Once the resonance dispute had been settled, the arch was said to divide the tract into two cavities each with its characteristic resonance - the mouth formant and the throat formant. We know today that the tongue arch does not form the dividing constriction and also that the formants have complex cavity affiliations. Nevertheless it is true that modification of the volume of the pharynx will affect the resonances of the vocal tract and that any articulatory modification of the pharynx is therefore acoustically relevant.

Attention was drawn by Stewart (1967) to the role played by the width of the lower pharynx in vowel harmony in the West African language Akan. This harmony difference is very similar to the tense-lax difference, although there are differing opinions as to whether they are both examples of the same phenomenon from the production point of view (Lindau et al. 1972, Lindau 1975). The advanced tongue root proposal claimed to cover both cases. The different tongue root positions for my English and Egyptian subjects have already been seen at Figs. 1 and 2. As already explained, the rule cannot hold for the low pharyngeal [ɑ, a] pair since the lower pharynx is now the location of the constriction.

What is the effect of varying the volume of the lower pharynx? Enlargement due to tongue root advancement occurs in the region of the epiglottis, that is, at about 2 to 4 cm above the glottis. Halle and Stevens recall Chiba and Kajiyama's observation that expansion of an acoustical tube in the vicinity of a sound pressure maximum in the standing wave for a particular natural frequency tends to lower that natural frequency. There is always a maximum in sound pressure distribution close to the glottis for all natural frequencies and in the case of F1 this maximum extends over the first 4 cm of the vocal tract. Hence expansion in this region always causes lowering of F_1. Halle and Stevens also point out that F2 has a pressure minimum at about 2 to 6 cm above the glottis for front vowels and a pressure maximum at about 4 cm above the glottis for back vowels. Expansion in this region will thus cause an upward shift of F_2 for front vowels and a downward shift of F_2 for back vowels. They note that these spectral differences are in the direction observed in acoustic data for tense-lax pairs.

The problem

In both natural speech and in the three-parameter model, the degree of constriction and the lower pharyngeal volume are largely inseparable. It is not therefore immediately apparent which, if either, of these two variables provides the greater contribution to the spectral differences between tense and lax vowels.

It is generally accepted that advancing the tongue root tends to bunch the tongue body towards the roof of the mouth. This manoeuvre thus simultaneously widens the lower pharynx and narrows the palatal or palatovelar constrictions. For the [o , ɔ]-like vowels with constricted upper pharynx, advancing the tongue root in the lower pharynx below the constriction is partially antagonistic to the narrowing of the upper pharynx by the contracting pharyngeal constrictor muscles. As recorded in Tables 2 and 3, I have found a difference of low pharyngeal width in this class but little difference in the degree of constriction (unlike other tense-lax pairs). For all the pharyngeal vowels, any tongue raising associated with tongue root advancement will diminish the volume of the bucchal cavity but at the same time such diminution is countered by any downward movement of the jaw.

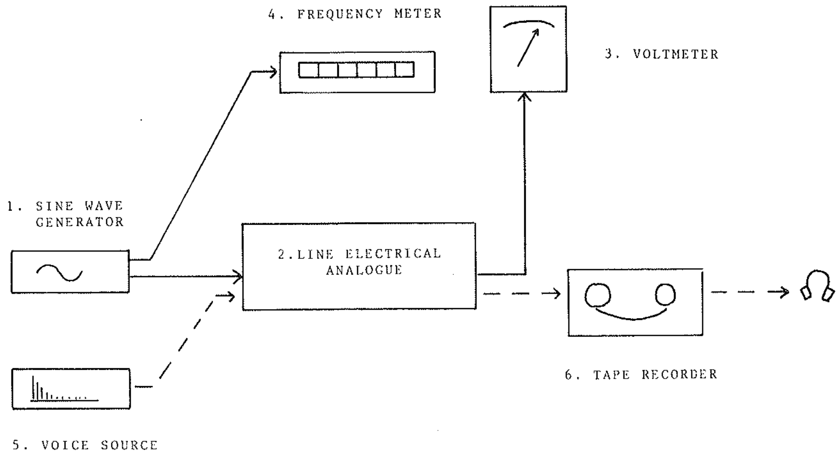


Fig. 4. For sweeping and measuring resonances, a sinus wave from the generator (1) is passed through the analogue LEA (2) to a voltmeter (3). Voltage maxima occur at resonance frequencies which can be read off from the frequency meter (4). For monitoring and recording synthetic vowel qualities, a voice spectrum from a voice source (5) passes through the analogue to a tape recorder (6).

CONSTRICTION	PALATAL				PALATO-VELAR		PHARYNGO-VELAR		LOW PHARYNGEAL	
VOWEL	i	ɪ	e	ɛ	u	ʊ	o	ɔ	ɑ	a
PALATAL	+	+	+	+	+	+	–	–	–	–
VELAR	–	–	–	–	+	+	+	+	–	–
PHARYNGEAL	–	–	–	–	–	–	+	+	+	+
OPEN	–	–	+	+	–	–	+	+	+	+
ROUND	–	–	–	–	+	+	+	+	(–)	–
TENSE	+	–	+	–	+	–	+	–	+	–

Table 4. A matrix showing how the different articulatory components are combined. Each component is defined in the text and by the values given in Tables 2 and 3.

In the three-parameter model, the equation that models the area function relates the opening of the passage above the tongue to the volume of the lower pharynx in a similar fashion to natural speech. Consequently, the different degrees of constriction at Fig. 3 are linked to corresponding pharyngeal differences. It is impossible to say whether the spectral reduction illustrated by this figure is the result of widening the constriction, narrowing the lower pharynx or both (if so in what proportions?). However, we have in the electrical vocal tract analogue a tool that permits us to alter the values of these variables at will. The underlying principle of the experiments reported below is to alter the vocal tract area function in steps from one configuration to another and to note the spectral difference arising from each step.

Method

By careful examination and analysis of motion X-ray films as outlined above, I have isolated the component gestures used by the human speaker to shape the vocal tract. Realistic modifications can be made to a vocal tract replica (a mid-saggital outline of a vocal tract) by reproducing the gestures of natural speech. This has resulted in a building kit that consists of a vocal tract (maxilla and pharynx), a mandible, a tongue for palatal constrictions, a tongue for palatovelar constrictions, a tongue for pharyngovelar constrictions, a tongue for low pharyngeal constrictions, a larynx that can be lowered 5 or 10 mm, sets of lips (spread, plain, slightly rounded, well rounded) and a tongue blade that can be depressed. These components are put together according to the matrix at Table 4.

Open is defined as a jaw-opening larger than 10 mm. For the experiments a jaw-opening of 14 mm was used. Non-open is a jaw-opening smaller than 10 mm. An opening of 8 mm was used.

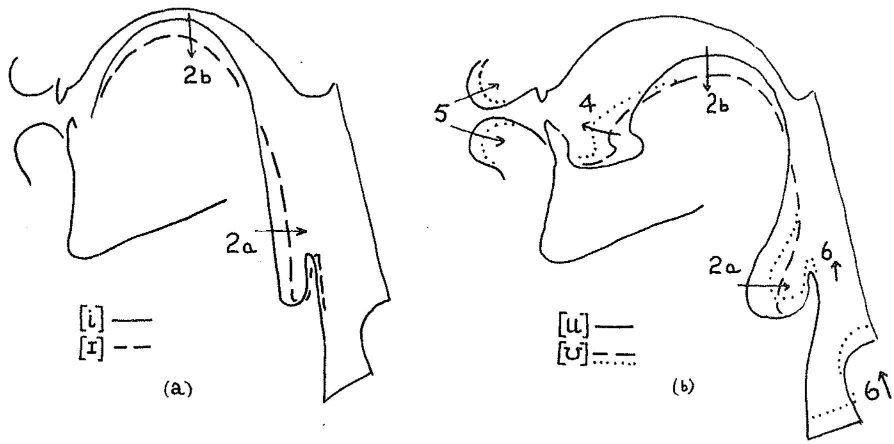


Fig. 5. Modifications made to the model profile for (a) palatal vowels and (b) palatovelar vowels.

For all tense vowels except low pharyngeal, the tongue root was advanced and the tongue body raised. This narrows the constriction of palatals and palatovelars. The constriction of the pharyngovelars is not altered. For the low pharyngeals, the tongue was drawn further into the pharynx to narrow the constriction. For rounded vowels, the larynx was lowered, 10 mm for tense and 5 mm for lax. The lips were more rounded for tense, less rounded for lax. The tongue blade was depressed more for tense rounded vowels, less for lax.

For each configuration, the cross-distances along the tract were transformed into cross-section areas using conversion data published by Sundberg (1969) for the palatal and upper pharyngeal region and by Fant (1960) for the lower pharyngeal region. The area functions thus obtained were then set on the electrical analogue and the resonances measured (Fig. 4).

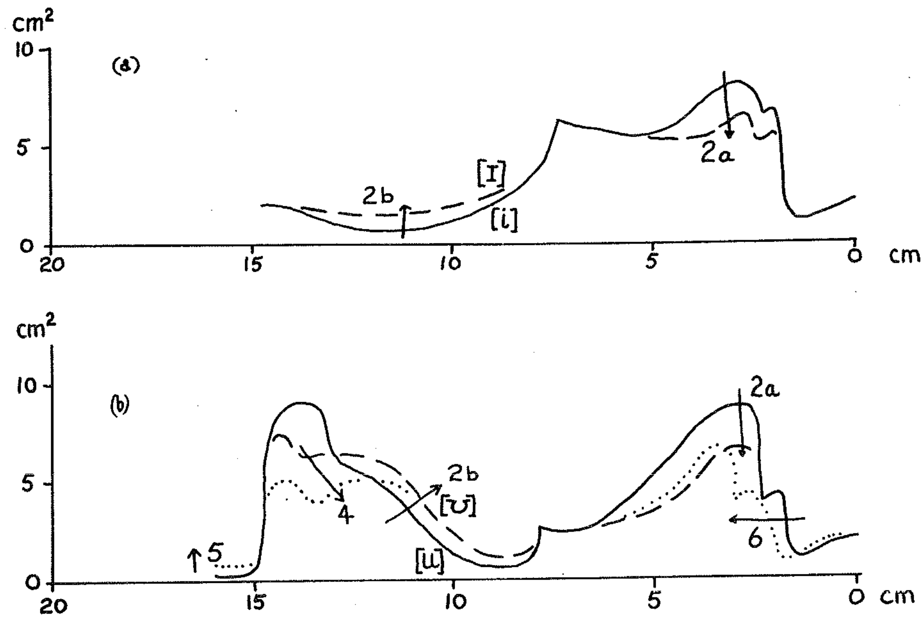


Fig. 6. Area functions for the configurations at Fig. 5(a, b).

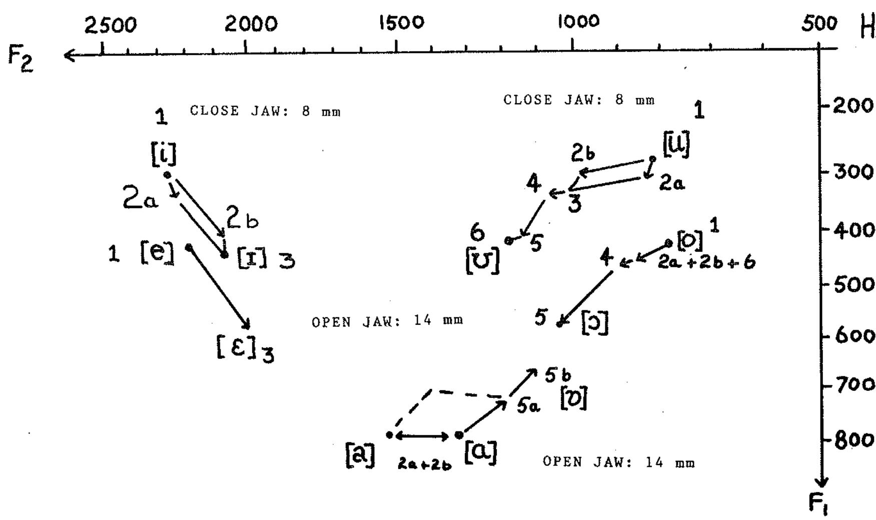


Fig. 7.

The spectral consequences of making the articulatory modifications illustrated at Figs. 5, 6 9 and 10. (1) is the initial tense configuration, (2a) retracted tongue root, (2b) lowered tongue arch, (3) the sum of 2a + 2b, (4) less depressed tongue blade, (5) less rounded lips, (6) less depressed larynx.

The same notation has been used for modifications for all vowels: (1) the initial tense vowel contour, (2a) retracted tongue root, (2b) widened constriction, (3) the sum of 2a and 2b, (4) less depressed tongue blade, (5) less rounded lips, (6) larynx less depressed by 5 mm.

Palatal constrictions

A tense [i] configuration was altered to a lax [ɪ] configuration (Figs. 5a and 6a) by lowering the tongue relative to the mandible. To avoid the necessity for compensatory movements, the same jaw-opening (8 mm) was used for both. The results were as follows (see also Fig. 7):

Retracted tongue root	F_1	+20 Hz	F_2	-20 Hz
Widened constriction	F_1	+90 Hz	F_2	-200 Hz

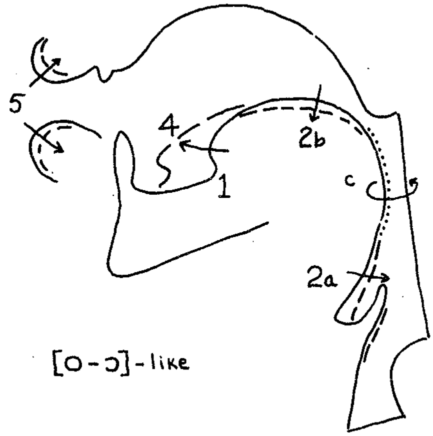
Both are in the right direction, but the contribution of the narrowed pharynx was small compared with that of the widened constriction.

The experiment was repeated for [e-ɛ] , using the same tongue profiles relative to the mandible but with a jaw-opening of 14 mm. A similar result was obtained.

Palatovelar constrictions

In addition to the different constriction sizes and tongue root positions between [u] and [ʊ] there are also differences of laminal depression, laryngeal depression and degree of rounding. The jaw-opening was 8 mm for both vowels. The modifications are illustrated at Figs. 5b and 6b and the results at Fig. 7.

Retracted tongue root	F_1	+25 Hz	F_2	+15 Hz
Widened constriction	F_1	+15 Hz	F_2	+185 Hz



	2a narrower lower pharynx	2b lower tongue arch	c narrower constriction	4 less laminal depression	5 less lip rounding
F_1 Hz	+20	+7	-10~15	+10~20	+100~130
F_2 Hz	+15	+30	-70	+40~80	+100~200

Fig. 8. Modifications made to the model profile for [o,ɔ]-like vowels and the spectral consequence of each with reference to the initial configuration.

Both are in the right direction. Here too, by far the largest contribution came from the widened constriction.

Fig. 7 also shows that the sum of these two modifications (point 3) is barely half the maximum possible spectral difference. Raising the tongue blade (4) and raising the larynx 5 mm (6) made moderate contributions to F_2 (+45 Hz and +35 Hz respectively) whereas relaxing the lips slightly (5) added as much as 80 or 90 Hz to both formants.

Pharyngovelar constrictions

Fig. 8 illustrates similar modifications for [o, ɔ] -like

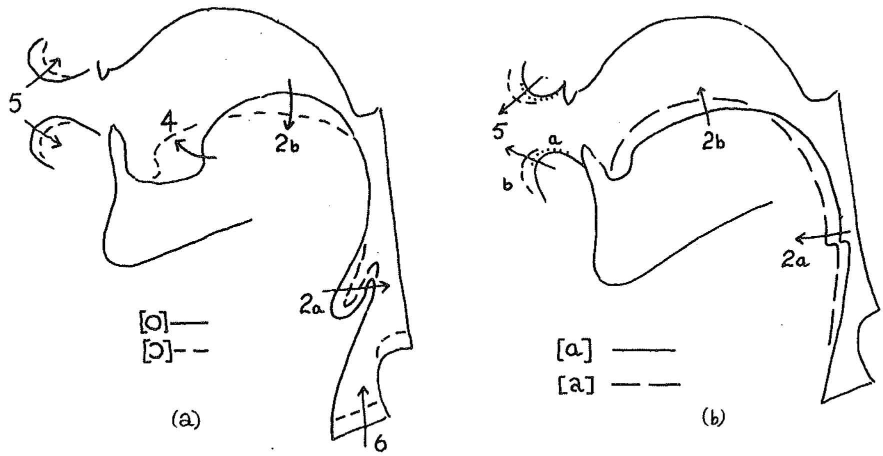


Fig. 9. Modifications made to the model profile for (a) pharyngovelar vowels and (b) low pharyngeal vowels.

vowels and gives the results. The jaw-opening was 14 mm. Modifications were made one at a time, always with reference to the same initial configuration. Both the retracted tongue root (2a) and lower tongue arch (2b) yielded small contributions. Narrowing the constriction from 1.0 cm^2 to 0.65 cm^2 lowered F_1 and F_2. Any tendency for [o] to have a wider constriction (cf. Table 2) is therefore spectrally disadvantageous to the contrast and constitutes a penalty that must be made up by some other factor (e.g. 2a+2b, 4). Less lip-rounding (5) produced a considerable spectral difference.

Figs. 9a and 10a illustrate stepwise modifications from [o] to [ɔ] with the same 0.65 cm^2 constriction for both (i.e. no penalty this time). The jaw-opening was 14 mm. The results are given at Fig. 7. Factor (5) (less lip-rounding) yielded as large a spectral difference as all the other factors (2a+2b+6+4) together.

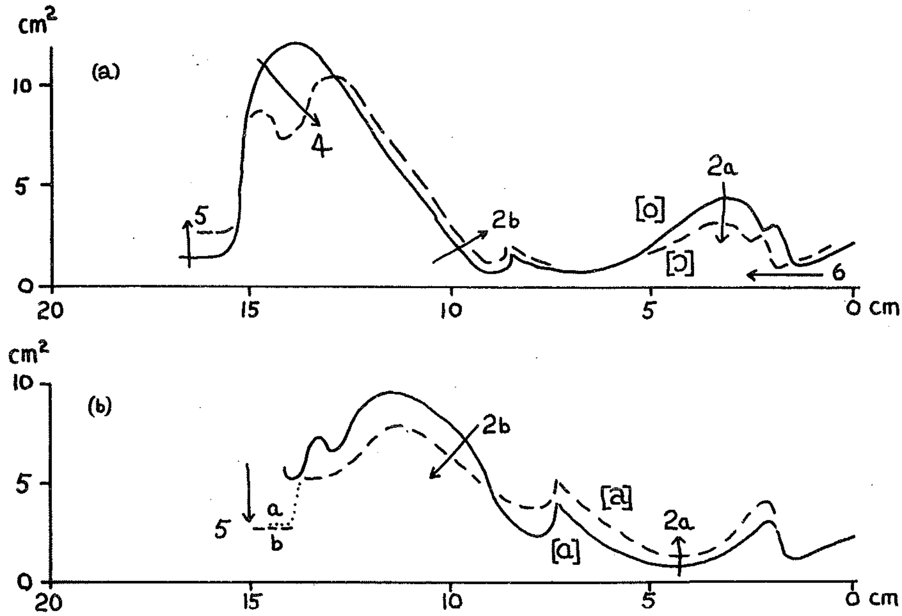


Fig. 10. Area functions for the configurations at Fig. 9(a, b).

<u>Low pharyngeals</u>

Figs. 9b and 10b illustrate modifications from an [ɑ] configuration to an [a] configuration. The jaw-opening was 14 mm. Spread lips (basic configuration) and neutral (5a) were applied to both since examples of both vowels with either lip position occur in natural speech. In addition, slightly rounded lips (5b) were applied to modify [ɑ] to [ɒ] . This is a grave variant of [ɑ] that occurs for Swedish /a:/ in some dialects. The results are given at Fig. 7.

The consequence of widening the constriction from 0.65 cm^2 for [ɑ] to 1.3 cm^2 for [a] was to raise F_2 by at least 200 Hz, with either spread or neutral lips. The difference between spread and neutral lips was about 80 Hz for F1 and 130 Hz for F2. Other experiments indicated that each 2 mm increment to jaw-opening adds 15-25 Hz to F1.

Discussion and conclusions

The results show that variation of the pharyngeal cavity yields a relatively small contribution to the spectral difference between tense and lax vowels. The very much larger contribution from variation of the degree of constriction is almost sufficient in itself for the spectral contrast, at least for the spread-lip vowels. In the case of the rounded vowels there is an equally large contribution from lip variation between well rounded and slightly rounded. For the pharyngovelar vowels, tongue root variation is not involved in the creation of the degree of constriction, but it is necessary to keep the lower pharynx open and thus avoid confusion with the low pharyngeal vowels. Any tendency for the tense pharyngovelar vowel to have the wider constriction means there is a spectral penalty from the point of view of this contrast.

It is also clear that the terms tense and lax need to be more precisely defined. In particular, the traditional notion that lax vowels have more "central" tongue positions is irrelevant and unacceptable in view of the inadequacies and inaccuracies of the tongue-arching model (Wood 1975). Are there any features that are common to all tense-lax pairs?

Fant has observed that the vocal tract is less deformed (nearer to the uniform tube) for lax vowels. As a generalization this is true, except perhaps for the [o, ɔ]-like vowels. The area functions at Figs. 6 and 10 show this resonator difference (although these are model configurations, they are the result of realistic articulatory manoeuvres based on observations of real speech). The details of how and where the vocal tract is less deformed vary from pair to pair.

Tongue root advancement and consequent pharyngeal expansion have been observed for tense vowels. This difference is most obvious for the palatal and palatovelar vowels and can be clearly seen in the examples at Figs. 1 and 2. Raphael and Bell-Berti (1975) have found corresponding differences in EMG activity in the genioglossi for American English /i-ɪ, e-ɛ, u-ʊ/. The results reported at Fig. 7 are that pharyngeal expansion contributes relatively little to these spectral contrasts whereas varying the degree of constriction yields the greatest spectral difference. However, it is generally accepted that advancing the tongue root has the secondary effect of raising the tongue body. This manoeuvre therefore also perticipates in control of the degree of constriction in this set of vowels and remains very much acoustically relevant. For the pharyngovelar vowels, the tongue root also tends to be further forward for tense [o] than lax [ɔ], widening the small cavity below the constriction. The spectral consequence of this is small (Fig. 8) but it is the right direction. There has so far been no data published regarding any correlated EMG activity in the genioglossi for this pair of vowels. For the low pharyngeal vowels, the relationshiop is reversed - narrower lower pharynx for tense [ɑ]. The advanced tongue root rule cannot apply in this case.

It is also frequently said that tense gestures are more precise and have greater extent. Regarding precision, it is fascinating to watch a motion X-ray film and see the level of precision achieved for all vowels, tense and lax. In view of the magnitude of spectral difference that can be achieved by widening the constriction, the amount of widening is critical and the ranges given at Table 1 must be respected. Regarding the extent of the tongue gestures (which are in the direction of the tongue constriction) the degree of constriction is narrower for the tense vowel in all pairs except [o, ɔ]. Figs. 1 and 2 show how the tongue is raised further towards the hard palate for tense [i, e], further towards the soft palate for tense [u] and further into the lower pharynx for tense [ɑ]. The results reported at Fig. 7 revealed that this narrowing of the constriction is the major single lingual factor contributing to the spectral contrast.

For the palatal and palatovelar vowels, the genioglossi aid the raising of the tongue body. The differences of EMG activity in tense and lax vowels reported by Raphael and Bella-Berti are therefore in a muscle that is actively involved in the basic tongue gesture of these vowels. For the palatovelar vowels, the styloglossi are also involved to draw the tongue back to the soft palate. But Raphael and Bella-Berti reported no noteworthy difference of activity between tense [u] and lax [ʊ] in this pair of muscles. For all three pairs they also reported a clear difference of activity in the inferior longitudinal muscle, an intrinsic muscle that depresses the tongue blade and helps bunch the tongue. The consequence of this can be seen at Figs. 1 and 2 for these vowels. For the rounded vowels, this can yield an F_2 difference of 100-200 Hz (Figs. 7 and 8).

The corresponding active extrinsic muscle for the low pharyngeal vowels is the hyoglossus. There are no EMG investigations reported for this muscle but I would expect more hyoglossal activity for the narrower constriction of tense [ɑ] than for the wider constriction of lax [a]. X-ray tracings for many subjects also show a more depressed tongue blade for [ɑ] indicating that the same difference of inferior longitudinal activity probably applies to this pair too (e.g. Figs. 1 and 2).

How do the pharyngovelar vowels fit into this pattern? The tongue root is more advanced for tense [o] than for lax [ɔ]. The difference recorded at Table 3 is typical, but for this pair in particular the absolute measure depends on the size of the valleculae which can vary considerably between subjects (cf. Figs. 1 and 2). The active muscles for tongue root advancement (the posterior genioglossi) are not involved in the creation of the upper pharyngeal constriction (which requires tongue retraction, not raising). It is nevertheless necessary to keep the lower cavity open in order to avoid confusion with the low pharyngeal [ɑ, a]-like vowels. The tongue root advancing manoeuvre is therefore an essential component for the pharyngovelars. The constriction itself is presumably formed by the pharyngeal constrictors (including the glossopharyngeal fibres that insert into the sides of the tongue). As for all other tense vowels, it is spectrally advantageous for [o] to have as narrow a constriction as possible. Paradoxically, [o] tends to have a slightly wider constriction than [ɔ] and therefore suffers a slight spectral penalty (Fig. 8) that is disadvantageous to the contrast. This may be due to the partial antagonism between the forward movement of the tongue root and the rearward movement of the tongue body. Finally, the tongue blade is more depressed for tense [o] than for lax [ɔ]. Here too, we should once again expect to find differences in inferior longitudinal activity.

It is therefore very likely that the physiological and articulatory difference between tense and lax vowels lies in varying the degree of contraction of a muscle that is already actively involved for a pair of vowels - such as the posterior genioglossi for the constriction of the palatal and palatovelar vowels and for keeping the lower pharynx open in the pharyngovelar vowels, and the hyoglossi for the constriction of the low pharyngeal vowels. The spectral consequences are always in the right direction for the contrast, very much so for the differences of degree of constriction, less so for the differences of pharyngeal cavity size. There are also differences of tongue blade depression and tongue bunching for all pairs which can be ascribed to differences of inferior longitudinal contraction (this may be what Sweet meant by the "convexity" of the tongue). For the palatal and palatovelar vowels the bunching aids in controlling the constriction against the roof of the mouth. For the palatovelar and pharyngovelar vowels, tongue blade depression enlarges the bucchal cavity and lowers F_2. Both these effects are favourable to the spectral contrast.

In addition, there is the difference of lip-rounding - more for tense vowels and less for lax vowels. Fig. 7 indicates that this can account for half the spectral contrast between [u] and [ʊ] and between [o] and [ɔ]. This is coupled to similar differences of laryngeal depression. The spectral consequences of this are relatively small (Fig. 7 and Lindblom and Sundberg 1971) but they are in the right direction.

Notes

1. See Fant (1960). I am endebted to Professor Gunnar Fant and Dr. Johan Sundberg of the Speech Transmission Laboratory, Royal Institute of Technology, Stockholm, for permission to use LEA and for assistance.

2. These films were made at the Röntgen Technology Unit of the University Hospital with the consent of Professor Olof Norman and the assistance of Dr. Thure Holm, Radiophysicists Gunnila Holje and Gudmund Swahn and Technician Rolf Schöner. The angiological laboratory was specially equipped for observing events in soft tissue such as blood vessels, and was therefore admirable for our purpose. In addition, the camera provides a synchronizing pulse that flashes on every tenth frame and which also appears alongside a patient's cardiogram. We recorded this pulse on magnetic tape together with the speech signal, on separate tracks. The film speed was 75 frames/second. X-rays were emitted in brief bursts, 3 msec per frame, which kept the radiation dose within the range 60-200 mrad per reel of film. Each subject was limited to one reel (40 seconds). I am endebted to Gösta Bruce and Per Lindblad for permission to include their films.

3. This summary is of necessity very scanty. More details will be given in a forthcoming thesis on the articulation of vowels.

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