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A RADIOGRAPHIC ANALYSIS OF CONSTRICTION LOCATIONS FOR VOWELS

SUMMARY

Vocal tract area functions estimated from 38 sets of X-rayed vowel articulations collected from the literature and from new X-ray motion films of English and Arabic speech reveal four constriction locations: along the hard palate, along the soft palate, in the upper pharynx and in the lower pharynx. Each location is appropriate for a definable class of vowel qualities, confirming the quantal nature of at least this aspect of vowel articulation. The acoustical, physiological and phonological implications are discussed. In a given phonotactic environment the precision of the constricting tongue manoeuvre was good. The only truly language specific difference was a preference for either the midpalatal or prepalatal location for palatal constrictions. The tongue muscles are found to be admirably situated for creating constrictions at the four locations.

1 INTRODUCTION

Since the second half of the 19th century, work on vowel articulation has largely been based on a model that prescribes for each vowel a unique tongue position in terms of height and fronting of the tongue arch. This model, initiated by Bell (1867), was rapidly adopted long before it could ever be subjected to experimental verification. It has never been validated, but it has been contradicted. For example, Meyer's (1910) plastopalatograms revealed unexpected tongue heights. The Bell model was conclusively discredited by Russel's massive X-ray study (1928) which failed to corroborate the predicted tongue arch positions. This was followed by several decades of advances in acoustical analysis and psycho-acoustical experimentation, which has led to proposals for purely auditory or integrated acoustical-auditory systems for describing vowels (Jakobson et al. 1952, Ladefoged et al.

1972, Lindau 1975, Lieberman 1976). During the same half century articulation was alrgely disavowed for vowel description. The confusing picture of vowel articulation obtained from X-ray studies and the theoretical possibility of producing the same sound in a variety of ways were seen as apparent proofs of the inconstancy of articulation and the multiplicity of compensatory adjustments. However, I suggest in this paper that the alleged inconsistancies are due to observation of the wrong articulatory variables (height and fronting) rather than to articulatory irregularity. There are important and relevant regularities in vowel articulation (Wood 1975a), one of which will be reported here: the number of locations where the vocal tract is constricted by the tongue.

The location of a major internal narrowing is a fundamental parameter of vocal tract configuration for vowels (Stevens and House 1955, Fant 1960). These authors, and Lindblom and Sundberg (1971), treated the length of the vocal tract as a continuum of constriction location for model explorations of vocal tract resonances. On the other hand, the articulatory model universally accepted from ancient India until the 19th century had divided vowels into [i-ɛ]-like palatals, [u-o]-like labiovelars and [ɑ-a]-like pharyngeals. These are precisely the three regions where Stevens (1972) found vowel spectra to be relatively insensitive to moderate displacements of constriction location. Examination of three-parameter model nomograms (such as Fant 1960, Fig. 1.4-11) discloses four locations with this property: at the hard palate and in the lower pharynx for spread-lip vowels and at the soft palate and in the upper pharynx for rounded vowels (Gunnilstam 1974). I have previously inferred the same four locations from the formant transition frequencies of West Greenlandic Eskimo vowels (Wood 1971): (i) along the hard palate for the [i-e]-like allophones of /i/ and the [ɛ]-like allophone of /a/, (ii) along the soft palate for the [u]-like allophone of /u/, (iii) in the upper pharynx for the [o, ɔ]-like allophones of /u/ and the [ɣ]-like allophone of /i/, and (iv) in the lower pharynx for the [ɑ, a, æ]-like allophones of /a/. All this varied evidence points to the use of a small number of discrete locations for the constriction. The analysis of X-rayed vowel articulations reported below confirms these four constriction locations without exception by 40 subjects in 13 languages.

This finding has important implications for the study of speech physiology and the evolution of the speech organs. If it is true that it is not acoustically relevant to utilize more than four constriction locations for vowels, and if speakers universally confine themselves to these four locations, then the tongue must have a far simpler task than has hitherto been assumed. We should expect to find manoeuvres directed towards each of the four constriction targets in the vocal tract and a suitable arrangement of tongue musculature for this purpose.

2 RADIOGRAPHIC MATERIAL

This investigation is based on 38 sets of mid-sagittal vocal tract tracings for 12 languages that have been reported in the literature during the past 75 years (Wood 1975a) and on two new X-ray motion films of Southern British English and Egyptian Arabic speech. Tracings from a third film (of West Greenlandic Eskimo speech) are also used to illustrate part of this report. These films were made at the angiocardiographic unit of the Lund University Hospital. The subjects were limited to one reel of 35 mm film each, which provided 40 seconds at 75 frames/second. The X-rays were delivered in one 3 msec pulse per frame. The absorbed radiation dose was 60-200 mrad/reel.

The Englishc subject read a randomized list of test sentences of the form ['pVti 'pVt ə 'pV̲ti,pVtə], where different test vowels were substituted for [V] and where [V̲] indicates the focus (intonation nucleus) of the sentence. The sentences were read at two different rates, yielding a total of 8 renderings of each of 10 different vowels. The Egyptian Arabic subject's sentences had the form ['bVti 'bVti 'bVta 'bV̲ti] and ['bVṭa 'bV̲ṭi] (with "emphatic" ṭ). These were read once and yielded 4 renderings of each vowel. For both subjects, the intervening lingual consonant and the weak vowels ensured that all test

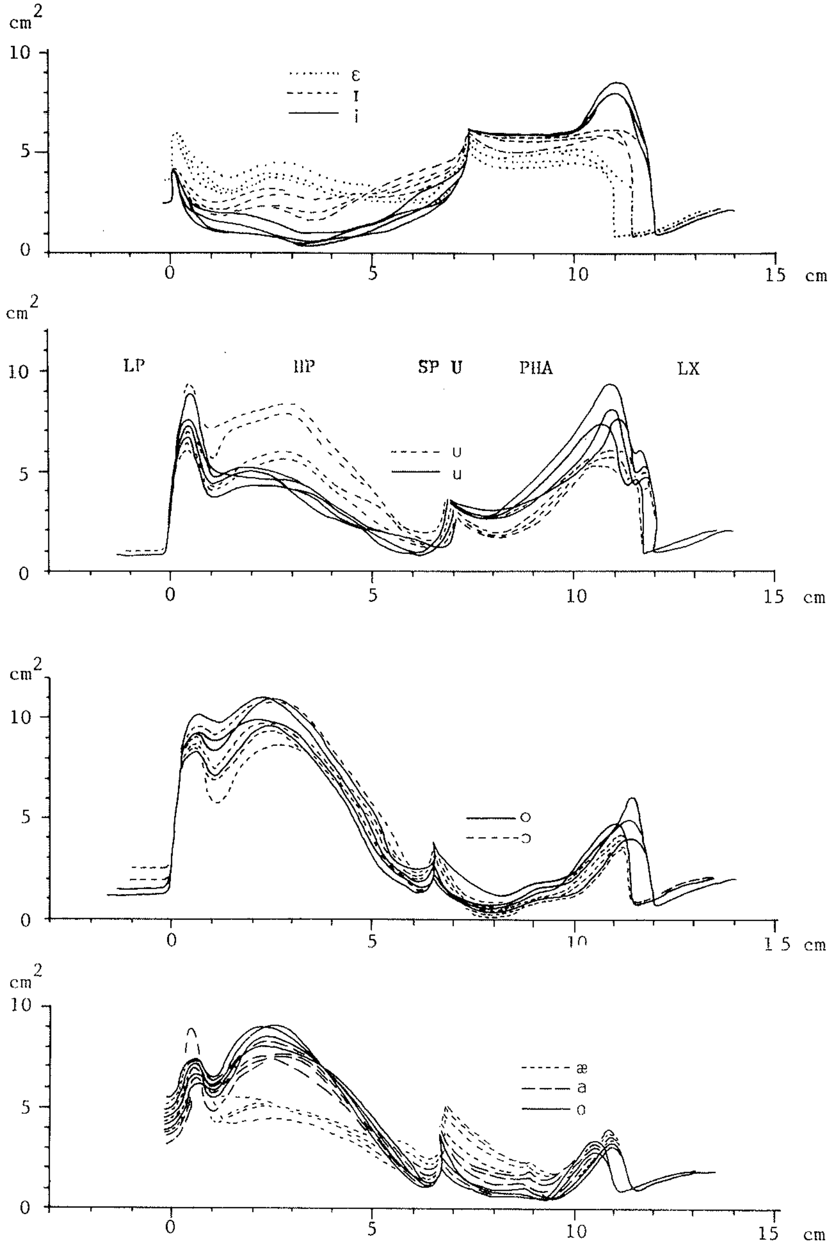

Fig. 1. The configuration of the vocal tract for vowels by the Southern British English subject, classed according to constriction location (hard palate, soft palate, upper pharynx, lower pharynx). The area functions are lined up at the central incisors (coordinate 0 cm). The letters identify parts of the vocal tract: LP lips, HP hard palate, SP soft palate, U uvula, PHA pharynx, LX larynx.

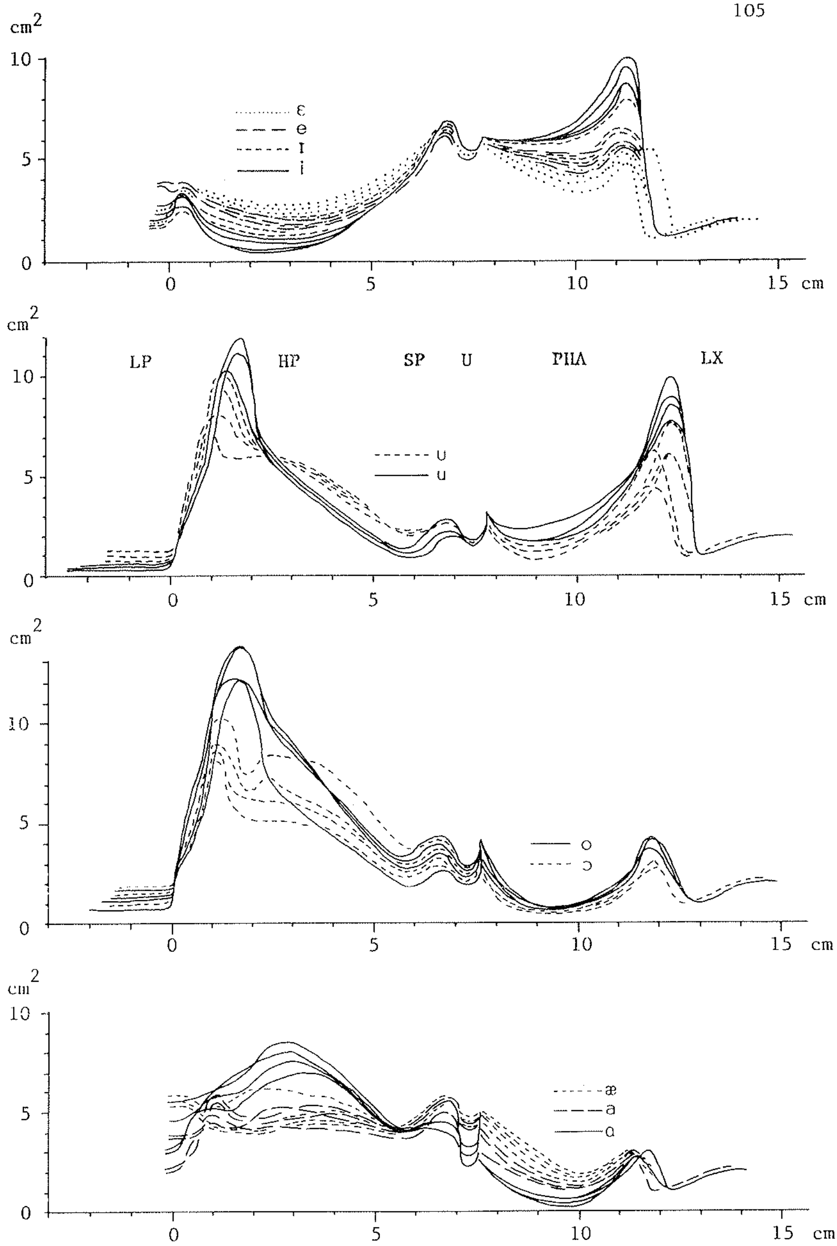

Fig. 2. Area functions for vowels by the Egyptian Arabic subject.

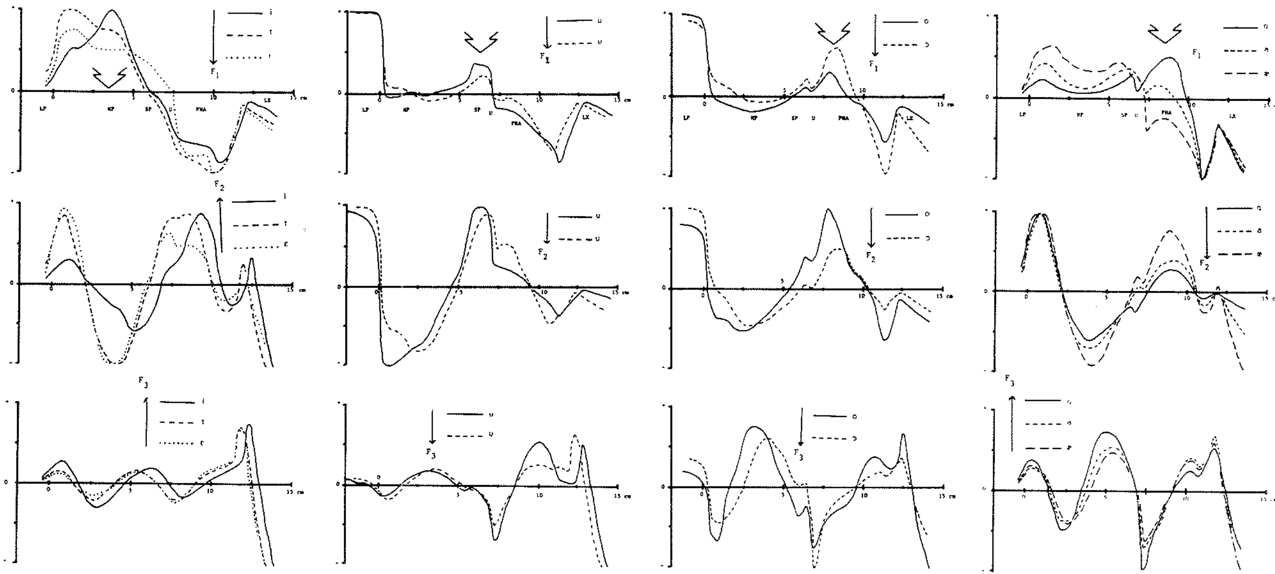

Fig. 3. The difference between the kinetic and potential energy distributions along the vocal tract, indicating the relative sensitivity of vocal tract resonances to local area perturbations. Local narrowing causes a resonance to fall or rise in proportion to the excess of kinetic or potential energy respectively (conversely for local expansion). English subject (cf. Fig. 1).

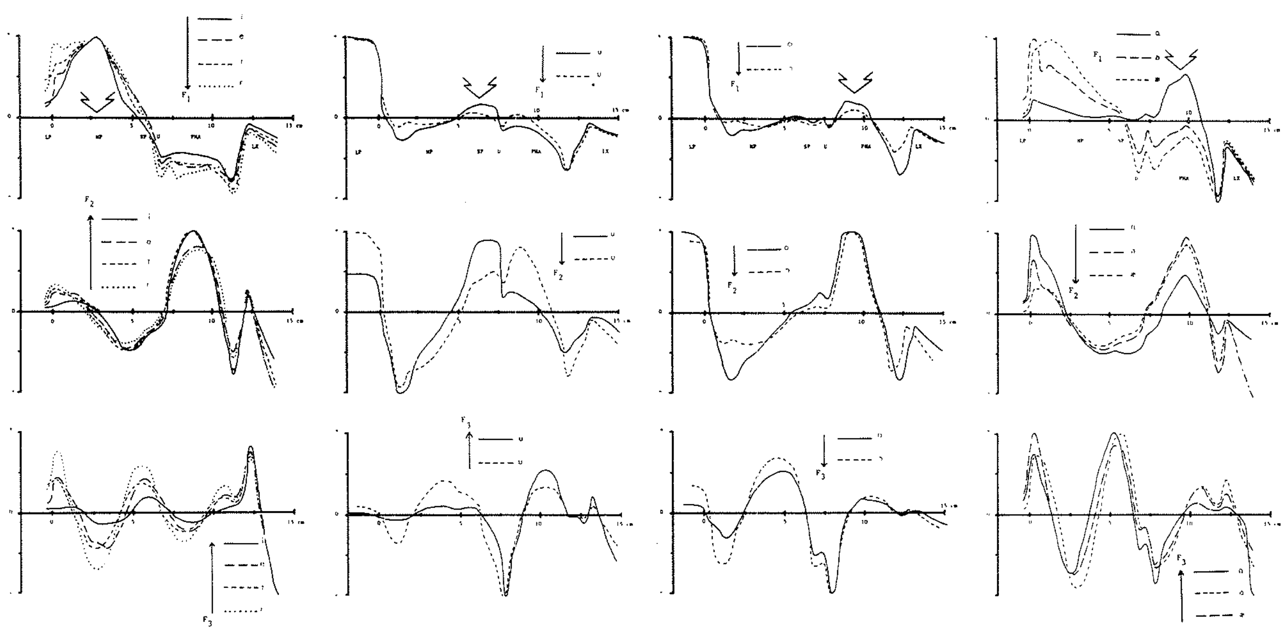

Fig. 4. Vocal tract resonance sensitivity functions, cf. Fig. 3. Egyptian Arabic subject (cf. Fig. 2).

that all test vowel articulations were independent. The number of tokens of each test item is important for statistical treatment (published sets of tracings rarely contain more than one token of each vowel).

The vocal tract area function for each rendering was estimated according to Sundberg (1969) and Lindblom and Sundberg (1971). Measurement of vocal resonance modes on a line electric analogue (LEA at the Speech Transmission Laboratory of the Stockholm Institute of Technology) indicated that estimated cross-section areas at the faucal isthmus in velar constrictions were too large. This will be discussed below (§ 6).

3 CONSTRICTION LOCATIONS

The striking tendency in all sets was that the tongue narrowed the vocal tract at one of four locations for vowels: (i) along the hard palate for [i-ɛ]-like and [y-ø]-like vowels, (ii) along the soft palate for [u-ʊ] and [ɨ]-like vowels, (iii) in the upper pharynx for [o-ɔ] and [ɣ]-like vowels, and (iv) in the lower pharynx for [ɑ-a-æ]-like vowels. Figs. 1 and 2 show area functions for my English and Arabic subjects. Area functions for the material collected from the literature were similar.

These are precisely those locations, referred to in the introduction, where resonance modes are insensitive to some displacement of the constriction. The fact that all subjects restricted themselves to these locations suggests that this preference is universal.

4 ACOUSTICAL CONSIDERATIONS

The combinations of F_1 and F_2 produced by constricting the vocal tract at each of the four locations can be studied by referring to three-parameter model nomograms. Fig. 5 is based on the Stevens and House (1955) nomograms and gives the frequencies of F1 and F2 generated by varying the degree of mouth-opening and the degree of constriction at each of the four constriction locations. Fig. 5 also contains the

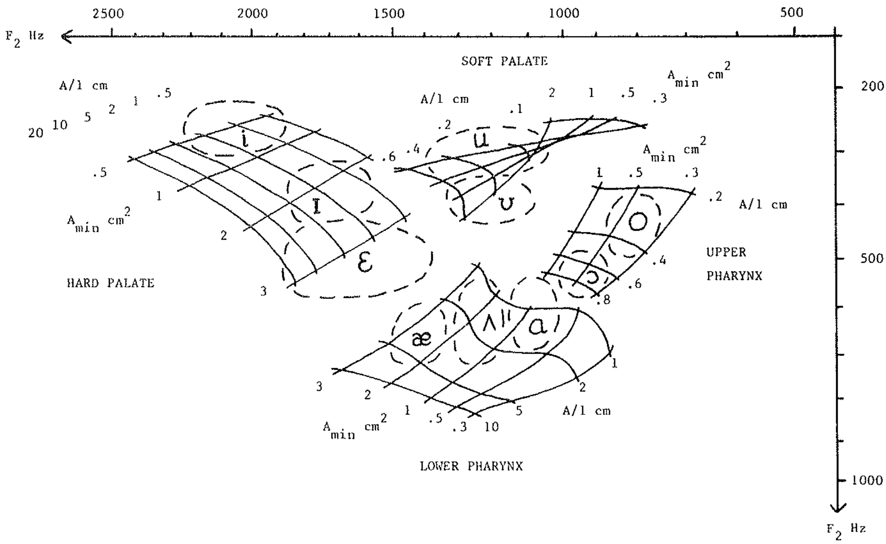

Fig. 5. The frequencies of F1 and F2 generated by the three-parameter model for the four preferred constriction locations, based on nomograms by Stevens and House (1955) (distance from source to constriction 12 cm for the hard palate, 8.5 cm for the soft palate, 6.5 cm for the upper pharynx, 4.5 cm for the lower pharynx). The superimposed vowel areas are from a sample of Southern British English speech recorded from the radio.

frequencies of F1 and F2 of stressed vowels in a sample of Southern British English speech recorded from the radio. The four constriction locations conveniently divide the entire F_1/F_2 space into four relatively unambiguous areas, each enclosing a definable family of vowel qualities. Within each area, the different spectra are obtained by varying the degree of constriction (corresponding to lingual and mandibular artculation) and the degree of mouth-opening (corresponding to labial and mandibular articulation). In natural speech the formant frequencies are also determined by tongue root movement in the lower pharynx, by tongue blade movement in the buccal cavity and by vertical larynx movement. These movements cannot be simulated by a three-parameter model independently of the three model parameters. Independent simulation is only possible by direct manipulation of the area

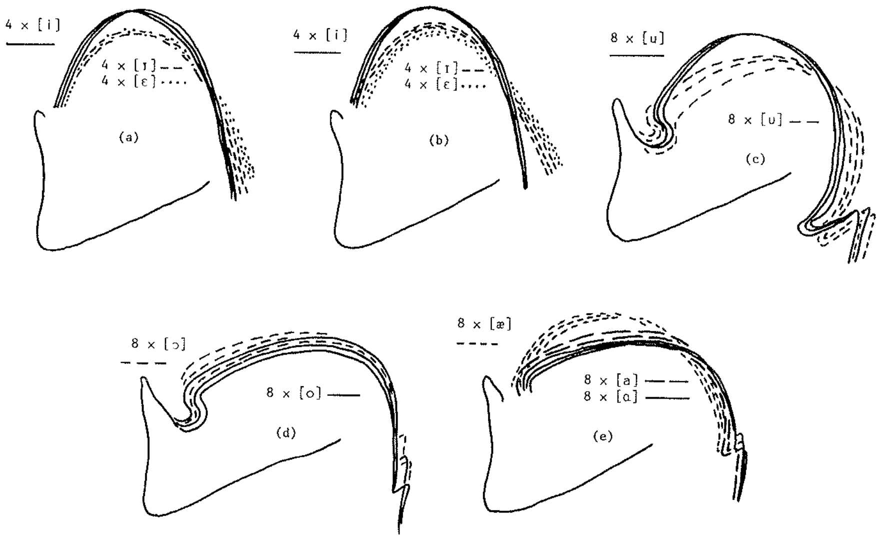

Fig. 6. Position of the tongue relative to the mandible for stressed vowels by the Southern British English subject, classed by constriction location. (a) slower rate, (b) faster rate, (c-e) both rates. The three profiles for each vowel represent the range of variation and the average position. Cf. Fig. 1. Note the mid-palatal posture for the palatal vowels (cf. Fig. 7).

function to reproduce the desired articulatory modification (Lindblom and Sundberg 1971, Mermelstein 1973).

The vocal tract is a single non-homogeneous pipe whose resonance modes are sensitive to local narrowing or expansion. All parts of the vocal tract contribute in varying degrees to each mode. The following laws help us understand the spectral consequences of each of the four preferred constriction locations. Firstly, local narrowing of the vocal tract will cause a resonance mode to rise or fall according as the perturbation is made in the vicinity of a sound pressure or volume velocity maximum in the standing wave for that mode (Chiba and Kajiyama 1941). The converse is true for local expansion. Secondly, the sensitivity of a resonance mode to a local area perturbation is related to the difference between the kinetic and potential energy at that point (Fant 1960, 1975; Schroeder 1967; Fant and Pauli 1975). A

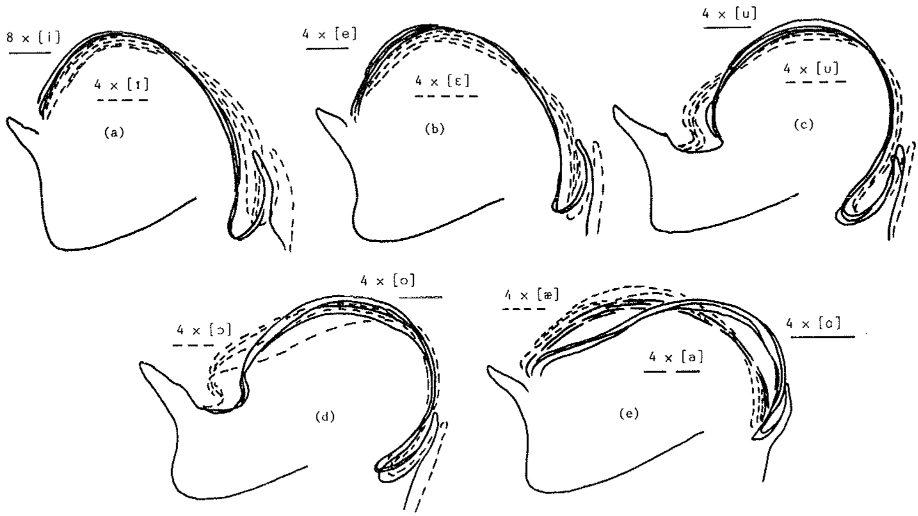

Fig. 7. The position of the tongue relative to the mandible for the stressed vowels by the Egyptian Arabic subject. Cf. Fig. 2. Note the prepalatal posture for the palatal vowels (cf. Fig. 6).

local expansion will cause a resonance mode to rise or fall in proportion to the excess of kinetic or potential energy respectively. Chiba and Kajiyama (1941), Fant (1960, 1975) and Mrayati and Carré (1976) give the volume velocity and sound pressure distributions for sets of Japanese, Russian and French vowels. In addition Fant (1975) and Mrayati and Carré (1976) give the energy distributions for their Russian and French sets. The sensitivity functions for my English and Arabic subjects are given at Figs. 3 and 4. All this data from different sources is strikingly similar for similar vowel qualities, as should be expected from the gross similarities of the corresponding area functions and the apparent universality of the four preferred constriction locations. It is therefore possible to generalize with confidence from this data to similar cases in other languages.

It is possible to predict from the volume velocity, sound pressure and

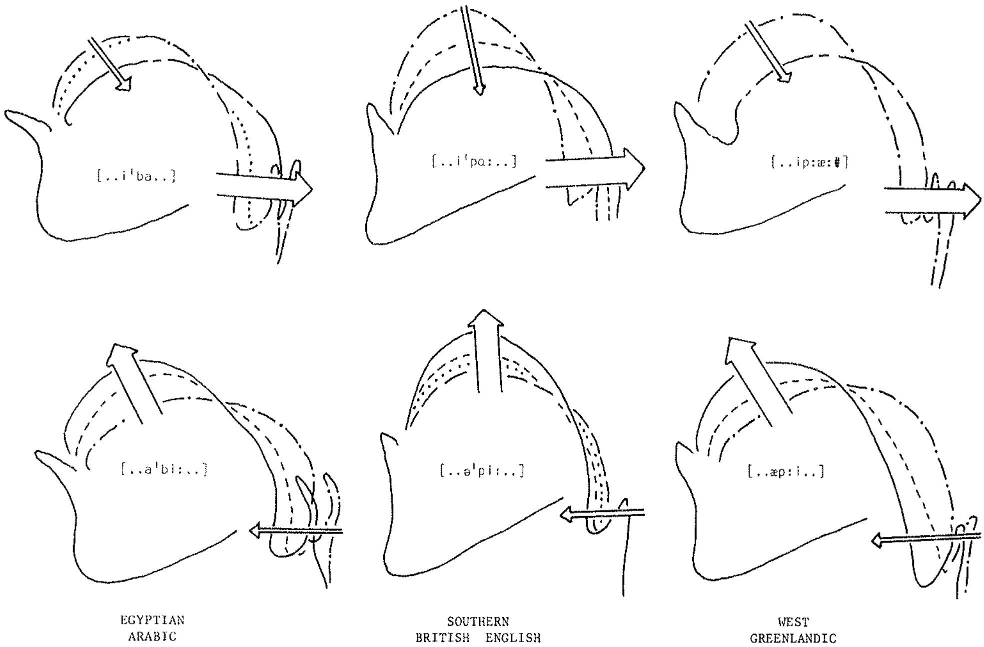

Fig. 8. The movement of the tongue relative to the mandible from a palatal [i], through [p, b] occlusion to low pharyngeal [ɑ, a, æ] (above) and vice-versa (below). The large arrows indicate the movement of the tongue body into the low pharyngeal or palatal constrictions respectively. The movement was sampled four times: first vowel — —, [p, b] occlusion ·······, [p, b] release - - - - , second vowel ——— .

energy distributions that limited but specifiable portions of the full F1 and F2 frequency ranges can be exploited at each of the four constriction locations (as exemplified at Fig. 5). These distributions also show why the formants are insensitive to slight constriction shifts at the four locations. The sound pressure and volume velocity maxima are not narrowly localized but range over extended zones. Consequently, resonance mode sensitivity to local narrowing or expansion does not alter appreciably through these zones (Figs. 3 and 4).

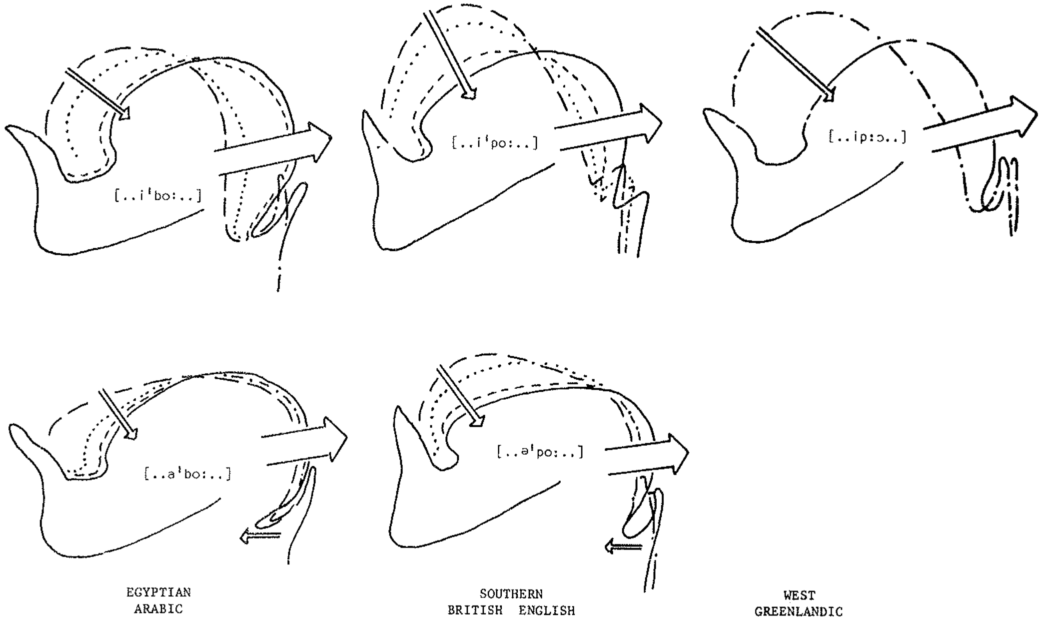

Fig. 9. The movement of the tongue relative to the mandible through [p, b] occlusion to upper pharyngeal [o] from a preceding [i] (above) and [a] (below). Cf. Fig. 8.

Since all parts of the vocal tract contribute to each resonance mode, vowel qualities within each of the four classes are not determined exclusively by varying the degree of constriction. It is particularly striking to note that in each of the four basic configuration types the tongue blade, the tongue body and the tongue root are in appropriate positions to narrow or expand the vocal tract precisely at sensitive parts of the F1 and F2 standing waves (Figs. 1, 2, 3, 4). Further, the extrinsic tongue muscles and the pharyngeal constrictors are admirably situated for this purpose (Fig. 11, § 7).

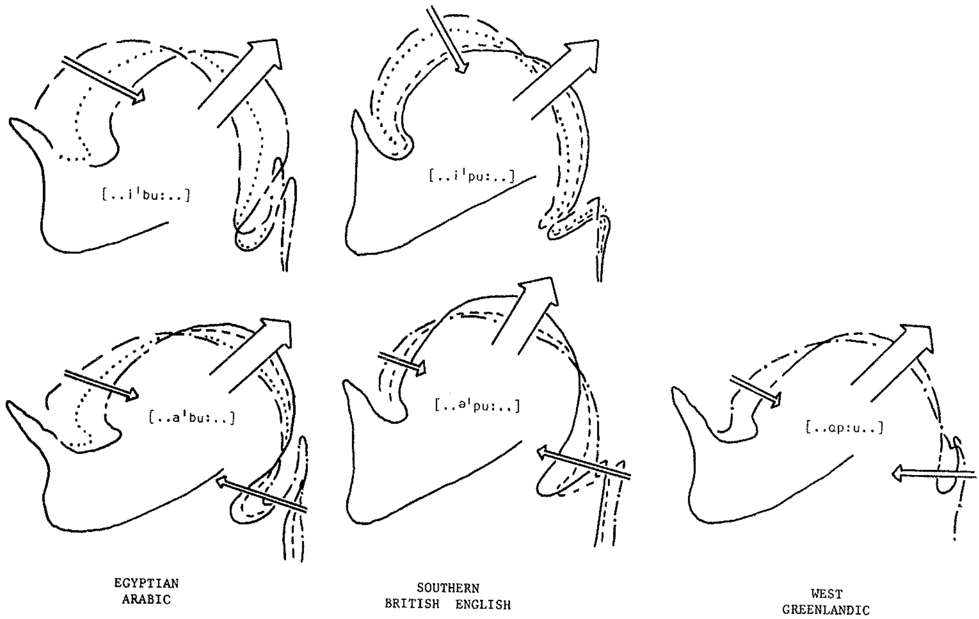

Fig. 10. The movement of the tongue relative to the mandible through [p, b] occlusion to velar [u] from a preceding palatal [i] (above) and low pharyngeal [a] (below). Cf. Fig. 8.

5 THE PRECISION OF THE CONSTRICTING GESTURES AND THEIR RELATION TO LARYNX HEIGHT

Stevens (1972) has pointed out the possible articulatory advantage of utilizing the regions of the vocal tract where formant frequencies are insensitive to some variation of constriction location. Such variation might arise from the coarticulatory constraints of normal connected speech. We can imagine the speaker may strive to maintain the same distance from the glottal source to the constriction, implying lingual compensation for vertical larynx movement by fine adjustment of the direction of the constricting tongue gesture. Alternatively, the

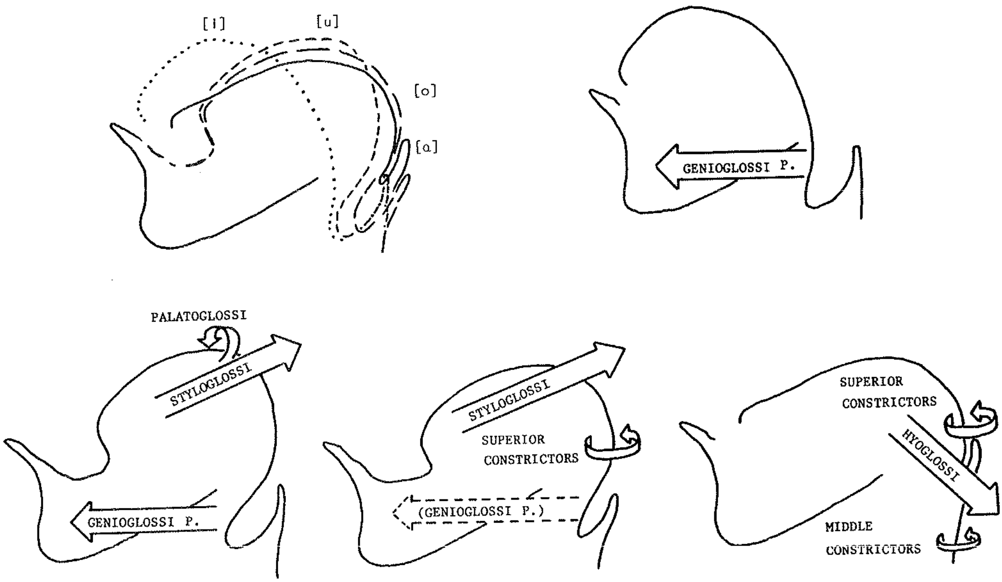

Fig. 11. The directions of contraction of the extrinsic muscles of the tongue and of the pharyngeal constrictors, arranged according to their presumed activity for the formation of the four constrictions.

speaker may constantly constrict the same part of the vocal tract, implying one location target disregarding the acoustical consequences of any variation of the vertical position of the larynx.

There is no evidence in the material reported here that speakers attempted to keep a constant distance from the glottal source to the constriction by making compensatory adjustments of the constricting gesture.

Figs. 1 and 2 are lined up on a fixed anatomical landmark, the central incisors. Variation of larynx height for any one vowel type is indicated by nonalignment at the glottal end. For these two subjects, the tongue was directed towards the same part of the vocal tract for each token of a vowel type with little variation between tokens and irrespective of any variation of larynx height. A possible exception was the low pharyngeal constriction of the [ɑ, a, æ]-like class which tended to keep a constant distance to the glottis. This is probably because the upper part of the epiglottis contributes to this constriction (observed visually by Chiba and Kajiyama 1941 and Lindqvist and Sundberg 1971). The epiglottis is linked to the thyroid cartilage so that some of the vertical movement of the larynx is transmitted to it. Consequently, the constriction remains at about 4 or 5 cm from the glottal source.

Individual constricting tongue movements are illustrated at Figs. 8, 9, 10. These show the movement of the tongue from one vowel constriction to another. The similarities between the three subjects (representing three unrelated languages) should be noted.

It may be more pertinent to ask if there is any opportunity to vary the constriction locations. Some of the muscles involved have a sphincteral function with a localized constricting effect (the palatoglossi and the pharyngeal constrictors, see Fig. 11). Only in the case of the palatal constriction, where there are no muscles contracting across the vocal tract to pull the tongue upwards, does there seem to be any freedom for varying the location target. There is further discussion of this below (§§ 6, 7).

The range of larynx heights between separate tokens of each vowel type by both subjects was about ±2.5 mm. The consequent variation of the distance from the glottal source to the constriction is within the acoustically tolerable limits and has little effect on the formant frequencies. The consequent variation of the overall length of the vocal tract also has little effect, about ± 2 % for F_2 of palatal vowels and much less for other vowels (Lindblom and Sundberg 1971, Wood 1975b). I assume that this random variation of larynx height from token to token reflects varying tensions of the extrinsic laryngeal musculature.

The larynx position does nevertheless appear to play an important roll in tuning the vocal tract. It is well known that the larynx is lower for rounded vowels than for spread lip vowels (Sundberg 1969). In the English and Arabic films the average larynx height was about 10 mm lower for "tense" [u, o] and about 5 mm lower for "lax" [ʊ, ɔ] than for spread-lip [i, ɛ]-like vowels. In the tracings collected from the literature, the larynx tended to be lower for [u, o, y, ø]-like vowels than for [ɨ, ɣ, ı, ɛ]-like vowels. By lengthening the vocal tract overall, this larger laryngeal depression contributes to the lowering of F_2 of the rounded vowels, especially those with a palatal constriction. But more important is the adjustment of the distance from the glottal source to the constriction. Fant's three-parameter model nomograms clearly show that when the lip-opening is narrowed there is a lengthening of the distance from the glottal source to each of the four regions where formant frequencies are not sensitive to small shifts of constriction location. The invariant tongue constriction locations still coincide with these regions in rounded vowels thanks to the lower larynx. Statistically, these adjustments are quantal. The larynx is depressed for rounded vowels (more so for "tense" than for "lax" vowels) and elevated for spread-lip vowels.

6 LANGUAGE-SPECIFIC DIFFERENCES OF CONSTRICTION LOCATION

The English and Arabic subjects had strikingly different constriction locations for palatal vowels (Figs. 1, 2, 6, 7). The English subject centred his constrictions midway along the hard palate about 35 mm behind the central incisors. The Arabic subject's constrictions were more anterior, about 27 mm behind the central incisors. This difference is reflected in the directions of their constricting tongue movements for palatal vowels (Figs. 6, 7, 8, 9). The American and British subjects in the collection of published tracings all had midpalatal constrictions centered at up to 40 mm from the incisors. Fant (1965) has pointed out a similar difference between "the Russian and Scandinavian [i] vowels which are prepalatal whereas the [i] is articulated more towards the midpalatal region in English", giving the former a sharper quality. The consequence of the less anterior mid-palatal constriction is a wider prepalatal part and narrower postpalatal part, which will both yield a lower F_3. The F3 standing wave has a prepalatal pressure maximum and a postpalatal volume velocity maximum. Figs. 3 and 4 show that F_3 is sensitive to modifications at both places in palatal vowels. It is interesting to note that most cases of prepalatal location in the collected material are from languages contrasting [i] with [y] or [ɨ] qualities. These contrasts are enhanced by having a maximally high F_3 in [i].

The estimated area functions also indicated a difference between the velar constrictions for [u] by these two subjects (Figs. 1 and 2). The maximum narrowing estimated for the English subject was opposite the uvula, the vocal tract widening out anteriorly along the soft palate. The Arabic subject appeared to narrow the dorsovelar passage near the front end of the velum. F_2 should not vary much for constriction shifts within this region but a model experiment on the analogue indicated that F_2 would rise about 120 Hz when this constriction is fronted along the whole length of the velum. Yet paradoxically the English subject's F_2 was the higher, 1000-1200 Hz against 750-900 Hz by the Arabic subject. F_2 is usually higher than 1000 Hz for [u]-like vowels in English (cf. Fig. 5) and lower than 1000 Hz for the graver [u]-like vowels of some other languages such as Swedish. The English subject had less close lip-rounding and a less depressed tongue blade, which according to analogue simulation would together more than counter any negative effect on F_2 from a slightly retracted constriction. But why is the Arabic subject's F_2 so much lower? Other analogue experiments indicated that the constricted dorsovelar passage needs to be extremely narrow if F_2 is to be lowered into the 700-1000 Hz range of a very grave [u] quality. Close lip-rounding alone is not sufficient. Narrowing of the dorsovelar passage is accompanied by narrowing of the top of the pharynx by the back of the tongue. The F2 standing wave has a volume velocity maximum extending right through the dorsovelar [u] constriction, with its peak in the pharynx immediately below the uvula. F_2 is therefore lowered not only by further narrowing of the dorsovelar passage but also by narrowing behind the constriction in the vicinity of the uvula. F2 of [u] has a considerable excess of kinetic energy throughout this region (Figs. 3 and 4) so that its frequency is extremely sensitive to narrowing all the way from the faucal isthmus to the top of the pharynx. A cross-section area in the constricted dorsovelar passage of at most 0.5 or 0.7 cm^2 would be necessary to keep F_2 below 1000 Hz. The area given for the Arabic subject has probably been overestimated. It is notoriously difficult to assess cross-section areas accurately in the velar region from cross-distances alone. The palatoglossal muscles (in the anterior faucal pillars) can function sphincterally, which would narrow the faucal isthmus transversely and contribute to the degree of constriction (cf. Fig. 11). If these muscles are active for [u]-like vowels (the evidence will be discussed below in § 7), then they could help provide the extra narrowing needed for the Arabic subject to lower his F_2 to well below 1000 Hz.

Of these two cases, the difference of location within the palatal region is most likely to provide a difference of vowel quality, by modifying F_3. For the velar region, any F_2 variation attributable to differences of constriction location is much smaller than any opposite variation from other articulatory variables (degree of constriction, degree of lip-rounding, tongue blade depression, larynx depression) and is therefore easily cancelled by them. The true difference between the [u] vowels of these two subjects is the degree of constriction throughout the velar-uvular region.

The amount of freedom available for varying the constriction location is again a crucial problem in this context. The sphincteral mode of the palatoglossi will narrow the vocal tract locally in [u]. If the styloglossi and palatoglossi (Fig. 11) together guide the tongue into position for [u], little freedom should remain for varying the constriction location. For the palatal vowels on the other hand, there are no muscles that contract across the anterior part of the vocal tract to pull the tongue up into position. The tongue has to be pushed up from below, which leaves greater freedom for determining the target of the movement.

7 PHYSIOLOGICAL CONSIDERATIONS

This section is devoted to how the four constrictions may be achieved. The discussion is based entirely on published material - anatomical descriptions supplemented by reported EMG results. The conventional view, extending back at least to Hellwag (1781), is that the tongue body is positioned for vowels by its extrinsic muscles. Hellwag listed the genioglossi (for palatals), the styloglossi (for velars) and the hyoglossi (for pharyngeals). In addition, the vocal tract is shaped by the palatoglossi (linking the tongue to the velum), the superior pharyngeal constrictors (including the glossopharyngeal fibres) and the middle pharyngeal constrictors. There will also be a contribution from the intrinsic muscles, especially the inferior longitudinals for tongue blade depression. The directions of contraction ascribed to these muscles are illustrated at Fig. 11. EMG data is still limited and has largely become available during the past decade.

Figs. 6 and 7 show tracings of the tongue profile relative to the mandible for a selection of vowels at each location. This presentation highlights similarities and differences of purely lingual articulation. There was little variation between different tokens of the same vowel by the same speaker.

Figs. 8, 9, 10 show the movement of the tongue to the different constriction locations from a preceding weak [i], [ə] or [a] through [p] or [b] occlusion. These are examples of the lingual manoeuvres that form the constrictions. The manoeuvres by each speaker are strikingly similar although they are for three unrelated languages.

Palatal vowels

There are no muscles that pull the tongue up towards the hard palate. The palatal tongue position is generally ascribed to contraction of the genioglossi, especially the posterior fibres. This is now being confirmed by EMG investigation (Harris 1971, Smith 1971, Raphael and Bell-Berti 1975, Miyawaki et al. 1975). These fibres pull the tongue root forward, widening the lower pharynx where both F_1 and F_2 are sensitive (Figs. 3 and 4). This contraction is also believed to push the tongue body upwards towards the hard palate where it narrows the palatal passage. The formants are also sensitive to the degree of palatal constriction, especially F_1. The mylohyoid muscles will also elevate the tongue body by pushing it up from the floor of the mouth but there is little agreement among authors as to whether they are used for vowels. They may, for example, provide the extra lift for a consonantal obstruction against the roof of the mouth. Any additional help in shaping the tongue in this class must come from intrinsic lingual muscles.

Labiovelar vowels

The [u, ʊ]-like and [o, ɔ]-like vowels constitute two separate classes according to constriction location, but it is convenient to discuss them together here. Figs. 6, 7, 11 show how the tongue is lower and more retracted relative to the mandible for [o] than for [u]. The same difference is true for all subjects in the collection of published tracings. The wider jaw-opening for [o, ɔ] will help lower the tongue away from the soft palate but it cannot unaided transfer the constriction to the upper pharynx. This must be done by the tongue itself.

The styloglossi draw the tongue upwards and rearwards towards the uvula. EMG investigations by Harris (1971), Smith (1971), Raphael and Bell-Berti (1975) have found the styloglossi active for [u]-like vowels. The similar brunched-up tongue postures of [u] and [o] suggest the styloglossi are also active for [o]-like vowels, but the data is very limited. Smith found styloglossal activity in cardinal [o:] but hardly any in cardinal [ɔ:]. Miyawaki et al. (1975) also studied the styloglossi but their results were unfortunately marred by artefacts.

The styloglossi can determine the general upward and rearward direction of lingual movement. But how is the tongue elevated towards the soft palate for [u] or retracted into the pharynx for [o]? For elevation there are two possibilities - the genioglossi pushing from below and the palatoglossi pulling from above. For retraction there are the superior pharyngeal constrictors. The hyoglossi, which draw the tongue down into the lower pharynx, have also been proposed in the literature for [o].

Harris (1971), Smith (1971), Raphael and Bell-Berti (1975) and Miyawaki et al. (1975) have all found the posterior genioglossal fibres to be active for [u]. Such activity can be deduced from the very wide lower pharynx for [u]. The posterior genioglossi should be less active for [o] since the tongue body is not elevated towards the velum and the tongue root is less advanced. At the same time there should be som activity for [o, ɔ] in these fibres in order to keep the lower pharynx sufficiently open for F_1 to stay in the 350-550 Hz range. There is also a difference of tongue root position between "tense" [o] and "lax" [ɔ]-like vowels (Wood 1975b) which indicates a difference of genioglossal activity between them. The posterior fibres of the genioglossi have so far been studied for [o] by only one group of investigators, Miyawaki et al. (1975). They found that the same electrode that picked up considerable activity for [u] also detected activity for [o].

Let us now turn to the palatoglossi. These are a very slender pair of muscles linking the dorsal part of the tongue and the soft palate. They lie in the anterior faucal pillars. They appear to have several modes of activity depending on what other structures or muscles happen to be doing (Lubker 1975), including (i) to draw the tongue towards the soft palate when the latter is firmly elevated by the palatine levators, and (ii) to act like a sphincter to narrow the faucal isthmus transversely. Both of these modes are relevant for the articulation of [u]-like vowels by (i) guiding the velar (styloglossal) movement anteriorly towards the soft palate, and (ii) controlling the degree of constriction there. It is well known that the velum tends to be most tightly closed agains the posterior pharyngeal wall during [u]-like vowels. An acoustic and perceptual explanation has usually been offered for this tight closure in an [u]-like configuration, based on the particular sensitivity of its oral resonances to nasal excitation and on the fact that contrastive nasality is rare for [u]-like vowels. However, a velum tightly closed by the palatine levators is a necessary condition for the sphincteral mode of palatoglossal function, which means there is a firm physiological constraint against nasalizing [u]. Any EMG activity recorded from the palatoglossi during [u] can only be due to the two modes quoted above from Lubker. Other modes are not applicable for [u] (opening the oronasal passage when the palatine levators are not contracting, or adjusting muscle length to accommodate a downward movement of the tongue). Fritzell (1969) found strong bursts of potentials in the palatoglossi during the transition from [f] to [u] in foolish and in [u] in the sequences [bu, du, gu] and [mu, nu, ŋu] (all with strong simultaneous levator contraction). Of Bell-Berti and Hirose's (1973) two subjects, one revealed no palatoglossal activity whatsoever, neither for [u] nor for nasals. The other had palatoglossal activity for all nasal openings and [k] and the largest bursts of all for [u]. The balance of all this data is in favour of palatoglossal involvement in the articulation of [u] with simultaneous contraction of the palatine levators.

For the retraction of the tongue into the pharynx for [o, ɔ], the most likely muscles are the superior pharyngeal constrictors (including the glossopharyngeal fibres) in view of their upper pharyngeal situation. Smith (1971) found the glossopharyngei active in [o, ɔ]-like vowels. MacNeilage and Sholes (1964) concluded from the activity picked up by surface electrodes from the back of the tongue that the hyoglossi were involved for [o]. But surface activity at that location could equally well have come from the glossopharyngei. The hyoglossi have so far not been investigated with electrodes inserted into the muscles themselves and their involvement is open to speculation in the absence of further data. Two factors probably rule out the hyoglossi for [o, ɔ]: (i) the upper pharyngeal [o, ɔ] constriction occurs where the glossopharyngei and the superior pharyngeal constrictors embrace the pharynx, and (ii) the moderately large cavity in the lower pharynx for [o, ɔ], necessary to avoid an unduly high F_1, precludes hyoglossal activity.

I conclude that the tongue is most likely drawn upwards and rearwards by the styloglossi for both the [u]-like and the [o]-like classes, and that this common movement is deflected towards the soft palate by the palatoglossi and the posterior genioglossi for [u]-like vowels, and into the upper pharynx by the superior pharyngeal constrictors and the glossopharyngei for [o]-like vowels. The genioglossi are active to widen the lower pharynx and assist in raising the tongue, more so for [u]-like vowels than for [o]-like vowels. The sphincteral function of the palatoglossi and the pharyngeal constrictors probably leaves little freedom for variation of these constriction locations.

Low pharyngeal vowels

For the [ɑ, a, æ]-like vowels, there is considerable general narrowing of the lower pharynx where F1 has high pressure and F2 a sensitive volume velocity maximum. The maximum constriction is in the vicinity of the epiglottis. The acoustical consequences are that F_1 is maximally high for all vowels in this class (at least 600-700 Hz with the large mouth-openings that are also typical of these vowels) and that the individual vowel qualities are distinguished by F_2 according to the degree of constriction (cf. Fig. 5). In contrast, the lower pharynx is less narrow for [ɛ, ɔ] configurations for which F_1 does not exceed about 550 Hz even with exaggerated mouth-openings.

The extrinsic tongue muscles that draw the tongue down into the lower pharynx are the hyoglossi. The inaccessibility of this pair has so far deterred investigators from attempting to insert electrodes. The pharyngeal constrictors are also frequently mentioned in conjunction with these vowels. The superior constrictors (including the glossopharyngeal fibres) retract the tongue and narrow the pharynx above the constriction. The middle constrictors, arising from the corni of the hyoid bones, narrow the pharynx at and below the constriction. Both Chiba and Kajiyama (1941) and Lindqvist and Sundberg (1971) have observed transversal narrowing of the constriction at the level of the epiglottis, indicating contraction of the constrictors. Smith (1971) found considerable activity from the glossopharyngeal fibres for cardinal [bɑ:] and [ba:]. Minifie et al. (1974) recorded the activity of the superior and middle constrictors to investigate differences of "tenseness" and "laxness" in [p, b] and reported no apparent differences between the vowels [i] and [a]. The activity they observed during [a] is expected for constrictor involvement in this vowel, but that observed for [i] is unexpected for a palatal vowel. A previous utrasonic scan (Minifie et al. 1970) had shown considerable inward displacement of the lateral pharyngeal walls (3-4 mm by the left wall) during the low pharyngeal vowels [ɑ, ʌ, æ] but little or nothing during [i, u], indicating constrictor activity for the former but not for the latter. Minifie et al. (1974) suggest that "had the EMG signals been integrated, discernable differences would have emerged" but they did not pursue the question further.

The availability of EMG data is least satisfactory of all in this class of vowels - nothing for the hyoglossi and occasionally contradictory for the pharyngeal constrictors. But the direct (visual) and indirect (X-ray, ultrasound) observations of movement are unanimous: the tongue is drawn into the lower pharynx and the pharynx is narrowed trasversely by inward movement of the lateral walls. This points strongly to involvement of both the hyoglossi to depress and retract the tongue and of the pharyngeal constrictors to narrow the pharynx generally and especially at and below the constriction. Narrowing of the lower pharynx is predictable from acoustic theory to raise F_1 to its maximum, above 600 or 700 Hz.

8 PHONOLOGICAL CONSIDERATIONS

All the data and discussion so far presented have clear implications for phonology. The preference for the four constriction locations is apparently universal. These locations are acoustically and physiologically significant. They divide the spectral space into four vowel quality families. The extrinsic tongue muscles are located just where they are needed to provide these constrictions and to narrow or expand the vocal tract at the sensitive parts of resonance mode standing waves. Phonetic processes that claim to describe phonemic contrasts, allophonic distributions, vowel shifts, morphophonemic alternations and so on in articulatory terms should reflect this unique way of utilizing the innate acoustical and anatomical properties of the vocal tract. The established tongue articulation model, which professed to describe tongue articulation in terms of the height and fronting of the tongue arch, failed to do this.

Notice also that the boundaries between the four families (Fig. 5) constitute the basic phonemic contrasts. In two-phoneme systems such as Kabardian (Halle 1970) there is a contrast between (i) [A]-like vowels produced with low pharyngeal locations and (ii) non-[A]-like vowels produced at the other constriction locations. In three-phoneme systems there are contrasts between (i) [A]-like vowels with low pharyngeal constrictions, (ii) spread-lip [I-E]-like vowels with palatal constrictions, and (iii) rounded [U-O]-like vowels with velar and upper pharyngeal constrictions. Five-phoneme systems have contrasts between (i) [A]-like vowels with low-pharyngeal constrictions, (ii) spread-lip [I]-like and (iii) spread-lip [E]-like vowels with palatal constrictions, (iv) rounded [U]-like vowels with velar constrictions and (v) rounded [O]-like vowels with upper pharyngeal constrictions. No further constrasts are obtained by varying the constriction location. Other modifications are utilized for additional contrasts, for example the degree of constriction, the degree of mouth-opening and the degree of lip-rounding.

An interesting phonological problem is how far and under what conditions the phoneme boundaries just outlined may be transgressed. For example, in Arabic and Eskimo there are spread-lip [ɨ] or [ɣ]-like allophones of /i/ with velar or pharyngeal constrictions carried over from adjacent consonant articulations. Again, umlauting involves an interchange of constriction location between (i) low pharyngeal [a], upper pharyngeal [o] and velar [u] and (ii) palatal [ε, ø, y] respectively. Similar interchanges of constriction locations are involved in instances of vowel harmony.

This approach to vowel articulation provides a new perspective to these types of phonological problem, whereas the established model cannot capture their true nature in terms of the height and fronting of the tongue arch. The ambiguities in the latter model regarding the relationships between parameter values, physiological activity, resonator configuration and spectral output means that it is powerless to explain central areas of speech production (Wood 1975a). The explanatory power of phonological theory will be greatly enhanced if the features of tongue articulation were instead derived from a comprehensive model based on the shaping of the entire vocal tract in a manner that directly relates physiology, articulation and acoustics.

9 CONCLUSIONS

1. There are four different places where the vocal tract is narrowly constricted by the tongue for vowels - along the hard palate, along the soft palate, in the upper pharynx and in the lower pharynx (Figs. 1, 2). This finding confirms Stevens's hypothesis that we seek to constrict the vocal tract for vowels at those places where F_1 and F_2 are least sensitive to variability of constriction location.

2. The vowels produced at these locations fall into distinct families: [i-ɛ, y-ø]-like, [u-ʊ, ṫ]-like, [o-ɔ, ɣ]-like and [ɑ-a-æ]-like respectively (Figs. 1, 2, 3, 4, 5). This supports Stevens's conclusion regarding the quantal nature of vowels.

3. The tongue assumes characteristic postures relative to the mandible that correspond to the four constriction locations (Figs. 6, 7, 8, 9, 10). Lingual movements to these postures can be unambiguously referred to muscular activity (Fig. 11).

4. There are documented examples of languages preferring either the prepalatal or midpalatal locations for the palatal constriction. However, the sphincteral function of the palatoglossi and the pharyngeal constrictors leaves little opportunity to vary the locations of the other three constrictions.

5. In a given consonant environment there is good precision of the

constricting movements. There was no evidence that the direction of the constricting gesture is modified to compensate for random verical larynx movement. But the structure of the epiglottis and the thyroid cartilage ensures that the low pharyngeal constriction automatically remains at about the same distance from the glottis.

6. When vowels are rounded, there is an increase in the distance from the glottis to each of the four regions where F_1 and F_2 are insensitive to small shifts of the constriction location. This is allowed for by depressing the larynx considerably for rounded vowels.

7. Articulatory features for use in phonology should reflect the preference for four constriction locations and the unique relationship between constricting tongue gestures, muscle situation and the degrees of sensitivity of vocal tract resonances to area perturbations at different parts of the vocal tract.

8. The approach to tongue articulation outlined here facilitates the building of a comprehensive description of speech production in which each of the successive stages (neuromotor, articulation, cavity, shaping, spectral output) are unambiuously related to each other. In contrast, the features of tongue arch height and fronting of the established model are ambiguous in these reapects and constitute a capricious medium for relating the different phases of speech production.

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