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THE WEAKNESSES OF THE TONGUE-ARCHING MODEL OF VOWEL ARTICULATION

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SUMMARY

Published X-ray tracings of vowel articulations are examined in the light of criticisms made against the tongue-arching model during the past 70 years. This corroborates the charges made against the model of failing to prescribe tongue position correctly. The implications of this failure are discussed. The constancy of vocal tract configurations, compared with the ambiguity of tongue arch position, points to a more suitable type of model for vowel articulation in which individual gestures combine to shape the vocal cavities to the resonator configurations appropriate to the sound quality.

CONTENTS

INTRODUCTION

The two-dimensional tongue-arching model has provided the predominant theoretical vowel articulation framework for phonetics and phonology during the past 100 years. There was never any real opportunity to test the physiological basis of the model before the introduction of radiology at the turn of the century provided the first means of investigating tongue positions and vocal tract configurations. Since then, a number of unexpected tongue positions have regularly been reported for some vowels, which raises serious doubts as to the <u>predictive capability</u> of the model. The following report contains an examination of 38 sets of X-ray profiles (published during the past half century or so), in order to ascertain how widespread and serious the apparently anomalous tongue arch positions might be. This is followed by a discussion of the implications of the results. Such anomalies need not necessarily be serious for phonetic theory - it might suffice to revise minor details of model design. However, current knowledge of vocal tract acoustics and the neuromotor level of speech production show respectively that the <u>explanatory power</u> and <u>physiological foundation</u> of the model are also very weak. The sum of these weaknesses is that the representation of vowel articulation provided by the model is not only inaccurate but also irrelevant to the processes of speech production. The model has constituted an unnecessarily weak link in current linguistic theory.

The main reason for the survival of the tongue-arching model to the present day has been the absence of a substitute articulatory model. Examination of the published tracings indicates that the vocal tract configuration is more constant than the tongue arch position. This matches the known regularity of spectral character. From this I conclude that the speaker is striving to create a definite target resonator shape appropriate to the intended quality and that it is reasonable to expect similar regularity at the articulatory and neuromotor stages. This provides a framework for a substitute model in which articulatory gestures, with known neuromotor activity, combine to create specific resonator shapes with known resonance properties. Since such a model is a more effective instrument of prediction and explanation, it will yield more realistic phonetic solutions to phonological problems. Phonology has therefore much to gain from adopting such a model in place of the tongue-arching model.

There has always been a school of phonetics during this same period that has expressed scepticism over some or all of the attempts to describe speech in articulatory terms of any sort. Its adherents have instead emphasized that speech communication is possible because definite sound qualities are heard and understood by a listener. They have therefore insisted that speech should be described in acoustic or perceptual terms. Some, especially towards the end of the 19th century when there was bitter rivalry between "acoustic" and "organic" schools, wished to shun articulation altogether. Others have since then continued to disregard articulation on the grounds that a speaker can utter a sound in a variety of ways, this inconstancy providing an apparent proof of the irrelevance of articulation. However, articulation is undeniably a necessary stage in the speech chain that merits description not only for its own sake but also because it is an indispensable link in speech communication between speaker and listener. Phonetics requires a comprehensive account of speech production and not a one-sided description restricted to any single phase of speech communication.

THE HISTORICAL BACKGROUND

The tongue-arching model portrayed vowel articulation in terms of two dimensions, the vertical and horizontal movement of the top of the tongue hump, by which vowels could be located in a Cartesian coordinate system (or, as D. Jones put it [1967: § 151], "by means of a system similar to the latitude and longitude principle used in geography"). Each vowel was said to have its own tongue position coordinates in the high/low and front/back dimensions, and a complete vowel system appeared as a polygon whose shape was characteristic for that language. It seemed perfectly natural to discuss vowel systems in geometrical terms by referring to the spatial relationships between points in the polygon. Other articulatory variables were often disregarded in the simple two-dimensional portrayal since they were said to be correlated with tongue arch coordinates for positions in the vowel polygon - for example, rounded front vowels have been described as "slightly retracted" relative to their unrounded counterparts, lax vowels "centralized" relative to the corresponding tense vowels, and so on.

Prior to the introduction of the tongue-arching model (in fact, ever since antiquity) vowel production had been understood in terms of three distinct tongue gestures (aimed at the pharynx, hard palate or velum), jaw opening and lip position. These gestures could easily be seen but in the absence of adequate acoustic theory their spectral consequences could not be properly understood or even known.[1] The mid-19th century philologists and Christian missionaries, handicapped by their limited knowledge of vocal tract acoustics and by the impossibility of making quantitative investigations of internal articulation, had found it increasingly difficult to account for finer distinctions of vowel quality or to accomodate the unfamiliar vowel qualities that were being discovered in the languages of the world. The new tongue-arching model appeared far more attractive and superseded the ancient model during the second half of the 19th century. For some reason, it also gained the reputation of being more scientific than the ancient model. The new model was almost universally adopted by the new movements that dominated work in phonetics towards the end of the century - the neogrammarians, the language teaching reformers and the IPA - and while some controversy between supporters of the rival schools still lingered on, the ancient model hardly survived into the present century apart from newer editions of earlier works. Helmholtz (1863) had referred to the ancient model, and his book reappeared in a 6th edition in 1913. The same model was preferred by the laryngologist Gutzmann for his speech handbook (1909) and he still retained it in the 2nd edition in 1929. Russel (1928) found that the ancient model gave a better picture of vowel articulation and the shaping of the vocal cavities (although above all he preferred to describe vowels by their acoustic and impressionistic characteristics). But among phoneticians and phonologists, the ancient model was already lost.

There is a fundamental conceptual difference between the two types of model regarding tongue movement between front and back. The ancient model recognized distinct pharyngeal, palatal and velar gestures. In the early years of the 19th century it was common to portray the ancient model in the form of a tree (n.b. not a triangle) with velar and palatal series branching off from the basic pharyngeal configuration, in simplified form thus:

a
o   e
u   i

In practice, the tree was augmented with additional branches for rounded palatals and plain velars. Contrary to widely held belief, the insertion of these brances between those depicted above never implied intermediate tongue positions[2]. In contrast, the tongue was allowed free movement in any direction in the tongue-arching model and, in particular, the tongue hump was said to occupy any position along the front/back axis. The possibility of intermediate tongue positions between front and back was explicit. Bell (1867) recounted how, after a sleepless night spent puzzling over the articulation of the vowel of sir, he came upon the idea of the tongue not only rising up to the hard and soft palates but also centrally between them. At a stroke of the imagination he created a whole new series of vacant matrix cells for the "difficult" vowels. This invention was revolutionary. The next step - to envisage the front/back axis as a continuum with any number of positions - was easy. An essential component of the tongue-arching model was this division of the horizontal axis into at least three positions. Many phoneticians, believing in a concept of continuous advancement or retraction, claimed that small horizontal adjustments of tongue position yielded modified vowel qualities. They spoke of an "advanced" [i] or a "retracted" [e], for example. It was this feature - alien to the ancient model - that made it so attractive in the 19th century, providing a seemingly simple tool for describing finer or unusual contrasts of vowels.

Attempts were made to relate the tongue arch positions to the vowel spectrum. It was formerly believed that the top of the tongue arch was the limit of a buchal cavity in which a characteristic vowel resonance was formed, and later that the arch constituted a neck between a buchal cavity and a pharyngeal cavity, each with its own resonance. The role of varying tongue height and retraction was said to be to vary the volume, and hence the resonance, of the buchal cavity. Now that the acoustics of the vocal tract are better understood and the source-filter theory generally accepted (Chiba and Kajiyama, 1941; Stevens and House, 1955, 1961; Fant, 1960) we have learnt that this role attributed to the tongue arch was a misconception. The location of the top of the tongue arch below the palate is only indirectly (and not always predictably) related to the configuration of the vocal cavities and the true place of narrowing in the vocal tract (cf. Fant, 1960: §§ 2.32, 2.33). The true place of narrowing can theoretically occur at any point along the vocal tract although in practice it occurs at one of four - along the hard palate, along the soft palate, in the upper pharynx and in the lower pharynx[3].

The tongue-arching representation of vowel articulation was never confirmed - on the contrary, it was discredited in one of the first genuine opportunities for testing its validity (Meyer, 1910). From the 1860s until the introduction of radiology at the turn of the century there had been no means available for observing or measuring the shapes, positions and sizes of the internal articulators and cavities, apart from palatography or the mirror and probe. The articulatory hypothesis underlying the tongue-arching model was refutable in principle but in reality the means for testing it were not available for a further three or four decades. Grandgent (1890) had devised a novel method of fitting different sized discs into various parts of the vocal tract to measure its cross-section and the overall picture he obtained of the cavities was remarkably good. In particular he was one of the first to point out how the back of the tongue falls away sharply in palatal vowels, leaving a far larger pharyngeal cavity than anyone had hitherto reckoned with. For comparison, the speech physiologist Brücke's (1856) profiles, based on anatomical sections, had a distinctly bulging pharyngeal tongue outline for [i]. But the numerous repetitions of a vowel articulation necessary for Grandgent's method meant that his measurements were very coarse and concealed differences of tongue arch position smaller than a millimetre or so. They did not therefore show up the anomalous tongue heights that were later reported from X-ray investigations. Atkinson (1898) had used a similar probing method. Even more ingenious was Meyer's plastopalatographic method (1910) in which fine strips of metal foil suspended from a false palate were deformed by the tongue so that they retained an imprint of its contour. Meyer found that the tongue was lower for "lax" /ɪ/ than for "tense" /ē/ (German, Dutch and Swedish informants) contrary to expectations and contradicting the predictions of the tongue-arching model. Meyer published these results in the Festschrift honouring Vietor, who (1914) agreed that they showed earlier notions about tongue articulation to have been largely erroneous. Vietor announced his intention of altering his popular textbooks of phonetics but he never did so. Chlumsky (1913) received Meyer's work with caution. In particular he was unable to obtain good results with the plastopalatographic method.

The first X-ray inspection had been performed just before the turn of the century as soon as the new invention had become available (Scheier, 1909) and a little later it had become possible to photograph the image and thereby conserve a more faithful and accurate reproduction (Meyer, 1907). These authors had investigated tense German vowels, and the omission of the lax vowels meant they had no opportunity to observe the unexpected /ē – ɪ/ tongue height "inversion" subsequently discovered by

Meyer. Kruisinger (1925) noted that "high" /ī/ and "mid" /ē/ were equally "high" on Meyer's radiograms. Russel (1928) took his first radiograms in order to demonstrate to his students the tongue-arching model, but failed to obtain a set of tongue positions that were convincing enough for the purpose. After taking several thousand radiograms from over 400 subjects, he concluded instead that the model was fallaceous. In addition to the [ɪ - e] height inversion, Russel observed that [ɔ] was often lower than [a]. He availed himself of every possible opportunity to attack the model, e.g. (1935). On the other hand, Carmody's (1937) faith in the model was not shaken by the irregular tongue arch positions he had discovered in Holbrook's sets of radiograms (for example, that "low back vowels depend mostly on lip position for their distinctive quality and so must be merged into a vague field which bounds their variations", and again, that "English ʌ is too variable to locate without further material since in our two tracings it falls once inside the quadrilateral and once directly behind o"). He found it meaningful to superimpose tongue arch diagrams for different speakers and languages and to describe the differences in terms of advancement-retraction and raising-lowering. He dismissed criticism of the model as coming "unfortunately from teachers acquainted with phonetics only at second hand". I wonder what Russel, whom he had named, said to that. On the other hand, Russel's own references to dogmatic acceptance of "unproved theories founded on fantasy" and to "philologists and others unacquainted with scientific phonetics" doubtless also upset many scholars in the 1920s and 1930s. Nevertheless, lateral profile radiograms of the vocal tract did frequently seem to reveal tongue arch positions that were confusing rather than enlightening with reference to the tongue-arching model. Many investigators must have experienced misgivings if not direct disappointment over puzzling X-ray results after all the trouble, expense and (not least) dangers involved in their work.

Much of the criticism of the tongue-arching model in the 19th century was internal and was concerned with the definition of features and the correct feature specifications of particular vowels or with the design of the model. For example, Bell classified the vowel of English <u>let</u> as "low-front-narrow" while Ellis, Sweet and Storm preferred "mid-front-wide". There was controversy towards the end of the 19th century as to whether "height" referred to the mandible (the traditional view) or the tongue (the new view, referring to internal resonator configuration). Not until very recently (Lindblom and Sundberg, 1971) have the individual contributions of the jaw-opening and tongue elevation been assessed separately.

At the same time, there was external opposition, especially from those who insisted that since speech consisted of sounds it should only be described in acoustic or auditory terms. Lloyd (1890) deplored the hostile rivalry and mutual disregard between the "organic" and "acoustic" schools. He pleaded "it is evident to a dispassionate observer that there is here no true place for partisanship, that neither line of investigation ought rightly to exclude or overlook the other, but that each is necessary to the other's completeness". The supposed physiological foundation of the model was undermined by Meyer's work in the first decade of the present century and finally destroyed by Russel's in the 1920s and 1930s. In the 1940s there came a new attack from a different angle. Joos (1948: §§2.35, 2.36) insisted that those phoneticians who believed they could feel the tongue positions by some kinesthetic sense were the victims of self-deception. They were really judging the vowels by auditory impressions. A similar conviction had already been expressed by Russel, but Joos had spectral evidence to strengthen this view. Judgments of height are usually related to the frequency of the first formant and judgments of advancement-retraction to the frequency of the second formant. Further confirmation has been provided by the experiments of Ladefoged (1967: chapt. 2).

Although the tongue-arching model has been discredited for more than half a century, it has never been completely disavowed. It still occupies a central position in phonetic theory, both for teaching and research as well as for phonology, as a glance through the phonetics and linguistics manuals and journals will show. But Meyer's and Russel's results were embarrasing and the reactions varied. Meyer's own solution to the crisis was a proposal that "tense" and "lax" vowels differ in vocal fold presure and in air flow (1913). Chlumsky (1914) was critical and the idea was hardly taken seriously by other phoneticians. A rare exception was a philologist and master at the Imperial High School of Zaborze, M. Leky, who while on war service completed a treatise on phonetics in which airflow variation is given a central role (1917).

Many, like Kruisinga (1925) or Russel (1928), held that the acoustic school's impressionistic analysis of speech was the better way. It seemed that there was a far greater constancy in the spectral character of speech than in articulation. Many held that articulation, seemingly so variable, was irrelevant in contrast to the spectral constancy. This coincided with the advances in design of spectro-analysers and other acoustic instruments (Joos, 1948; Fant, 1958) and a new and hitherto largely unexplored field was opened up to determine the spectral character of speech segments for many languages and to discover the acoustic contrasts and cues preferred by listeners.

Others, either sceptical and preferring to wait and see, or wanting for something better, retained the tongue-arching model. Jespersen, in later editions of his phonetics handbook, faithfully reported the anomalous tongue heights found by Meyer and observed that vowel theory had been shaken. But hesitated to draw the consequences because of the subjectively felt affinity of [i] to [ɪ] and [e] to [ɛ] and he therefore retained the traditional view: "und wenn ich trotz aller Annerkennung von Meyers vorzüglicher Arbeit auch in dieser Ausgabe im wesentlichen die alte Lehre festgehelten habe, geschiet dies, weil m.E. der übereinstimmenden subjektiven Abschätzung vieler Beobachter auf Grund überaus zahlreicher Warnehmungen ein grosser Wert beizumessen ist". He hoped further investigations would be made and suggested that the behaviour of the dorsum of the tongue would turn out to be more important than the front for vowel articulation. Many phoneticians doubted whether experimental design and methods had been satisfactory. Chlumsky (1913) failed to reproduce Meyer's plastopalatographic results. Others feared that contrast chains and sustained utterances distorted the articulation of X-ray subjects, despite the assurances of practitioners like Russel (1928) or Gutzmann (1930), or public demonstrations by S. Jones (1929) who pronounced the name of the Welsh village Llanfairpwllgwyngyllgogerychwyrndrobwllllantisiliogogogoch with one silver chain along the tongue and another thorugh the nose and down over the velum. Meyer's results were rarely mentioned in other phonetics handbooks.[4] The model continued to enjoy popular acceptance.

Many have continued to rely on the model simply because it has provided a convenient abstract classification system fulfilling a foremost requirement of linguistics during this period however shaky the model of production on which the classifying features have been based. Any other set of features would have served equally well. Classification is an example of the lowest level of measurement, the nominal scale, where one-to-one transformations of the classifying labels are permissible. An abstract classifying system is consequently not affected by any errors of fact regarding speech production providing the categories remain intact. Scholars, whose only requirement has been for a classification system, have been able to continue, deaf to the theoretical crisis surrounding tongue articulation.

One reason for the retention of the tongue-arching model has been the lack of a substitute. Even recently, Ladefoged (1971; chapt. 8), after recognizing that the terms of the tongue-arching model are often not in accord with the physiological facts and that "it is difficult to understand how phoneticians could persist in considering that the traditional articulatory categories provide an adequate specification of vowels", has nevertheless once again retained the tongue-arching model in an elementary text book. He added the reservation that "in descriptions of vowels, although a pseudo-articulatory terminology may provide an adequate set of labels for auditory descriptions, we have seen that we do not have, as yet, a set of articulatory parameters which will specify vowel quality". In the purely acoustic tradition of phonetics, Russel had suggested a set of impressionistic features for describing vowel qualities. Similarly, there are the acoustic features of Jakobson et al. (1952) based on the spectral character of speech segments. The simplest acoustic alternative has been a one-to-one substitution of falling F_1 for "height" judgments and falling F_2 for "retraction" judgments (Joos, 1948; Delattre, 1951) or falling F_2-F_1 difference for "retraction (Ladefoged et al. 1971a). But for articulation, the ancient model displaced by the tongue-arching model belonged irretrievably to the unscientific past. Yet it is interesting to note that three of the acoustically relevant constriction locations in the vocal tract coincide with the three tongue gestures of the ancient model (pharyngeal, palatal and velar), showing the latter to have been a sounder view of vowel articulation than its 19th century opponents in the tongue-arching school were prepared to admit. There has been a slender tradition among acoustics theorists from Helmholtz through Paget and Russel to Chiba, Kajiyama, Stevens, House and Fant on which an alternative to the tongue-arching model may be based.

EXAMINATION OF PUBLISHED X-RAY TRACINGS

Methods and material

I have examined 38 sets of X-ray tracings of vowel articulations from 15 different languages (published during the past half century of so) in order to discover how widespread and serious the irregular tongue arch positions might be. If the anomalies are rare, they may be looked upon as accidentally deviant articulations that can be disregarded. If they occur more frequently, it will be necessary to consider just how misleading the tongue-arching model might be and to weigh the implications for phonology.

I have collected the following sets, whose authors covered a wide range of interests such as language teaching, linguistics theory, dialectology, acoustics, speech therapy, laryngology and so on:

Meyer (1907), German; Scheier (1909), German; Polland and Hála (1926), Czeck; Parmenter and Treviño (1932), Spanish; Carmody (1936), Holbrook's German; Carmody (1937), Holbrook's French (3), Spanish, Italian, Portuguese, Am. English (2), S. Br. English, Russian, Polish; Chlumsky et al. (1938), French; Sovijärvi (1938), Finnish; Chiba and Kajiyama (1941), Japanese, German; Mazlovà (1949), Zábřeh dialect of Czeck; Ohnesorg and Švarny (1955), Chinese (3); Skaličková (1955), Korean; Koneczna and Zawadowski (1956), Russian (4); Korlén and Malmberg (1959), Strenger's German; Strenger, Swedish; Hála (1959), S. Br. English; Fant (1960), Russian; Wängler (1961), German; Malmberg (1966), Strenger's Spanish; Perkell (1969), Am. English; Perkell (1971), Am. English; Pétursson (1974), Icelandic.

Each tracing has been photographed and enlarged to natural size. The tracings have been reproduced to a scale that provides overall vocal tract lengths in the range 15-19 cms (depending on the vowel) for male speakers and somewhat shorter for female speakers. Comparison of such features as cervicle segments, incisors and mandible, maxilla and hyoid bones ensured that all articulations in one set were reproduced to the same scale.

Some authors warned that it would be impossible to superimpose their tracings for comparison owing to distortion arising from different points

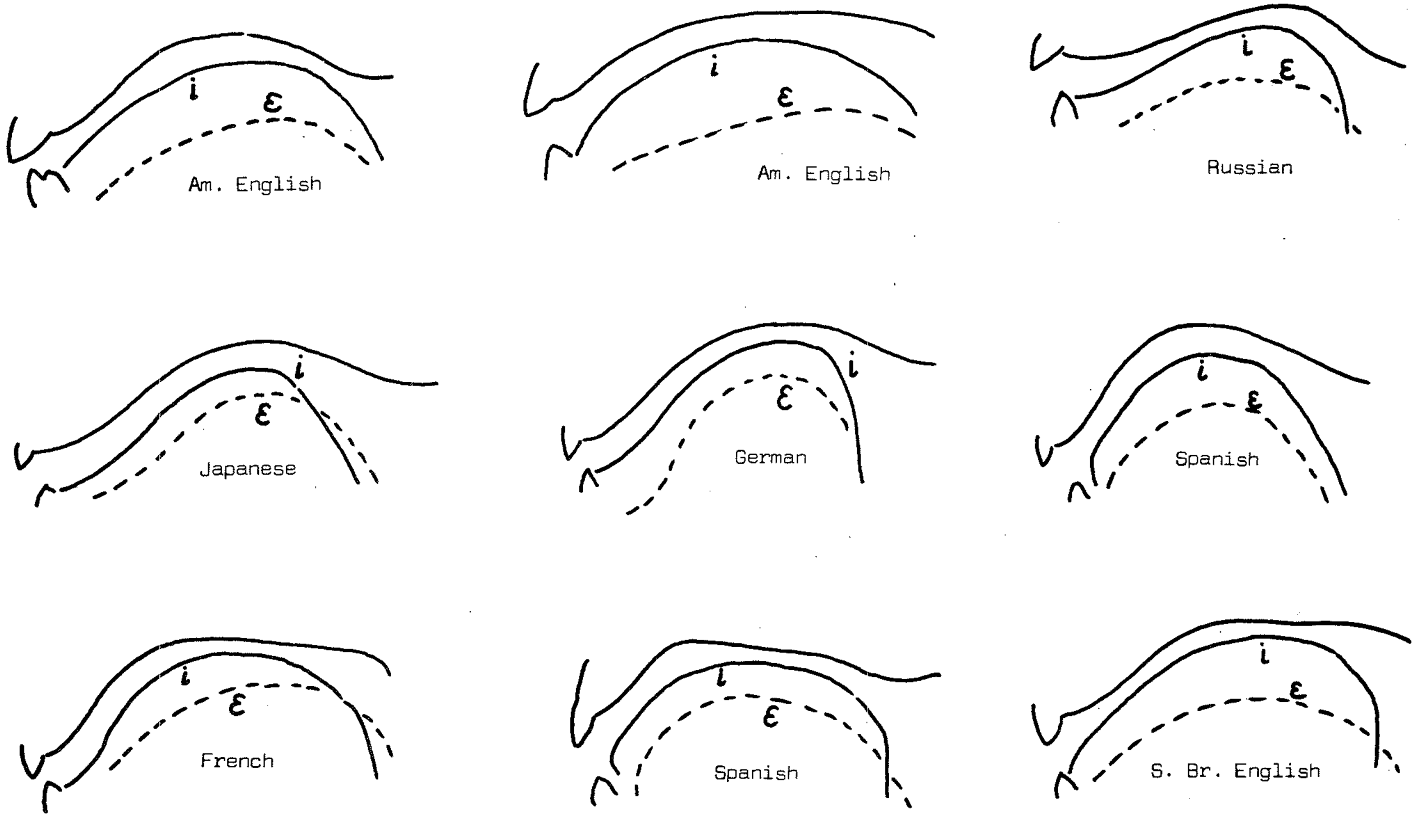

Fig. 1. A selection of [i] and [ε] profiles, illustrating how the tongue closely follows the individual shape of the hard palate (cf. also Fig. 2).

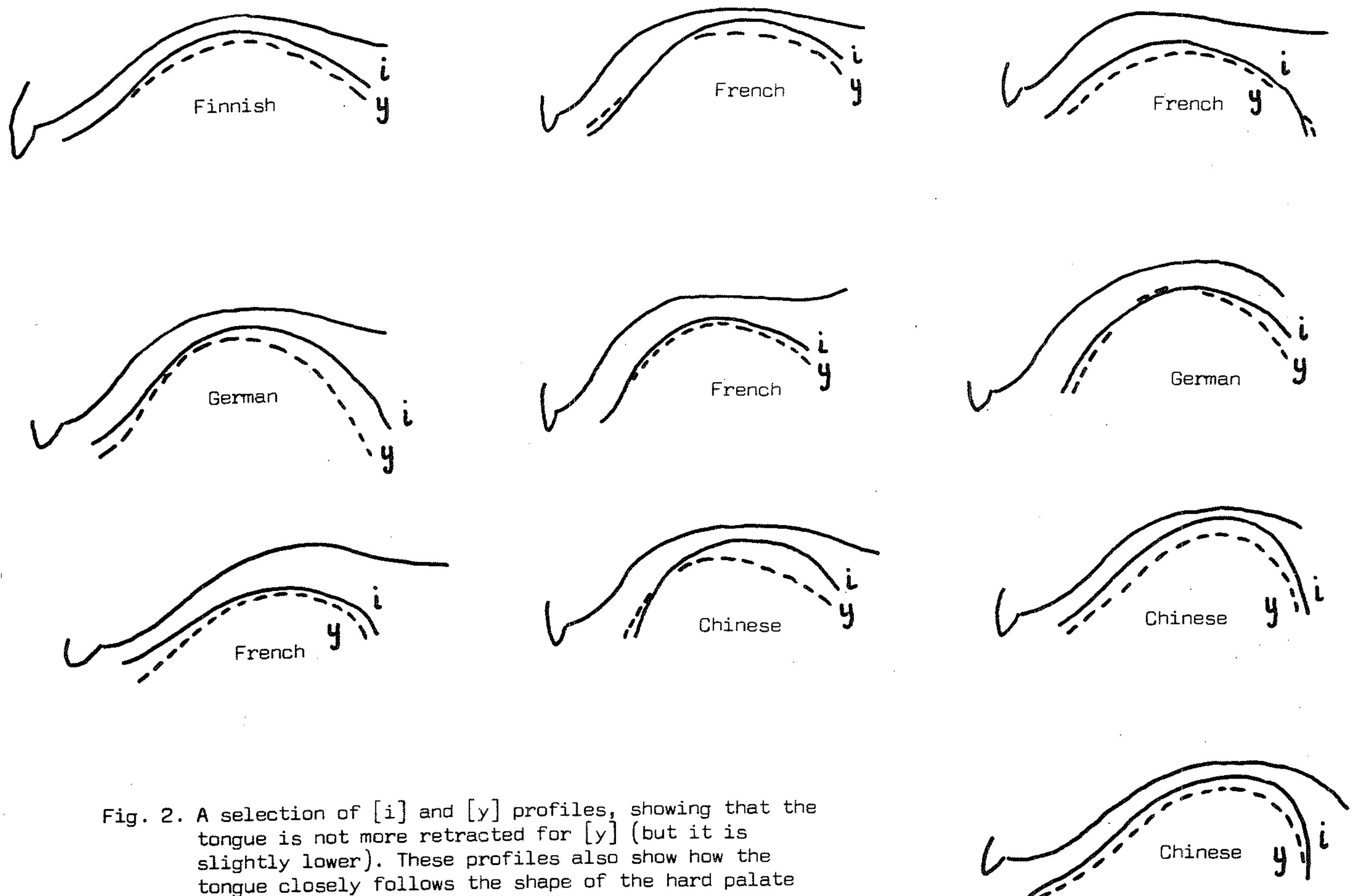

Fig. 2. A selection of [i] and [y] profiles, showing that the tongue is not more retracted for [y] (but it is slightly lower). These profiles also show how the tongue closely follows the shape of the hard palate (cf. Fig. 1).

of aim of the X-ray beam. After normalizing the scale of reproduction, I have hardly found this to be so. Differences between the relative sizes of the hard features on successive exposures are rarely larger than would be expected from simple random tracing errors. Distortion errors would not seem to be a major component of the total experimental error. On the other hand, tracings in some of the sets certainly cannot be superimposed exactly in the form published because their authors had used a different scale of reproduction for each separate picture.

I have used the vocal tract area function as a model for cavity configuration, the volume of a section of the tract being proportional to the cross-section area of that section. Distances across the vocal tract measured on the tracings have been transformed into cross-section areas according to two functions published by Sundberg (1969) for the palatal region and for the upper pharyngeal region. Sundberg's pharyngeal cross-distance/cross-area functions differ from others (Fant, 1960, Ladefoged et al., 1971). He argues that the side walls of the pharynx are drawn inwards when the cross-distance exceeds about 25 mm with the result that further sagittal widening of the pharynx produces a net reduction in the cross-area. The same procedure was followed by Lindblom and Sundberg (1971) except that this effect was not observed in the lower pharynx and they therefore used two functions for the pharyngeal region, one for above the epiglottis and one for the remainder. Following their example, I have also used a third function for the lower pharynx derived from data published by Fant (1960). The areas and lengths of the lip sections have been estimated with the help of the procedures and data given by Lindblom and Sundberg (1971).

Regarding the history of speech radiography and technical procedures, there are two comprehensive surveys, MacMillan and Keleman (1952) and Simon (1961). Standard sources of technical procedures for phoneticians in recent decades have been Subtelny et al. (1957) and Strenger (1968) while current cineradiographic techniques have been described by Moll (1960), Perkell (1969) and Kent (1972).

Tongue retraction

Fig. 1 contains tongue profiles for [i]-like and [ɛ]-like vowels from a selection of sets. The following features should be noted:

(i) There is wide variation of hard palate shapes between speakers from sharply domed to relatively flat.

(ii) The tongue of each speaker, irrespective of language, closely follows the contour of the hard palate for [i], leaving a very narrow passage (cross-section area about 0.5–1.0 cm^2).

(iii) Consequently, the top of the tongue arch may be further forward or further back for different speakers, depending on the shape of the hard palate.

In addition, the tongue profile for [ɛ] is also dominated by the contour of the palate, which still determines the location of the highest part of the hump. Essentially, as has been pointed out by Lindblom and Sundberg, the tongue profiles of [i] and [ɛ] for each speaker are very similar with reference to the mandible. Characteristic for [ɛ] is the wider channel along the palate (cross-section area about 3 cm^2). I conclude therefore that failure to consider the shape of the hard palate is a possible source of error that spuriously indicates "retraction" as a major difference when tracings for different subjects are being compared. See also Fig. 2 which contains a further selection of [i] profiles, this time related to [y].

The belief in several degrees of retraction has been further encouraged by incorrect articulatory interpretation of vowel spectra. It has been recognized for several decades that the traditional subjective judgment "retraction" was really based on auditory sensation and was related to the frequency of the second formant. Unfortunately, it has been too easy to assume the converse, that the frequency of the second formant will therefore reflect horizontal movement of the tongue (see, for example, Delattre 1951). The relationship between tongue movement and vowel spectrum is more complex. Fant pointed out that tongue <u>lowering</u> can cause F_2 to fall. This can be illustrated by an example from the published sets of X-ray tracings, the "tense-lax" quality difference between English or German /ī/ and /ɪ/ where the F_2 difference is some 300 or 400 Hz. The mandibular and lingual articulations of /ī, ɪ/ by Chiba and Kajiyama's German subject are given at Figs. 3 (a, d). These

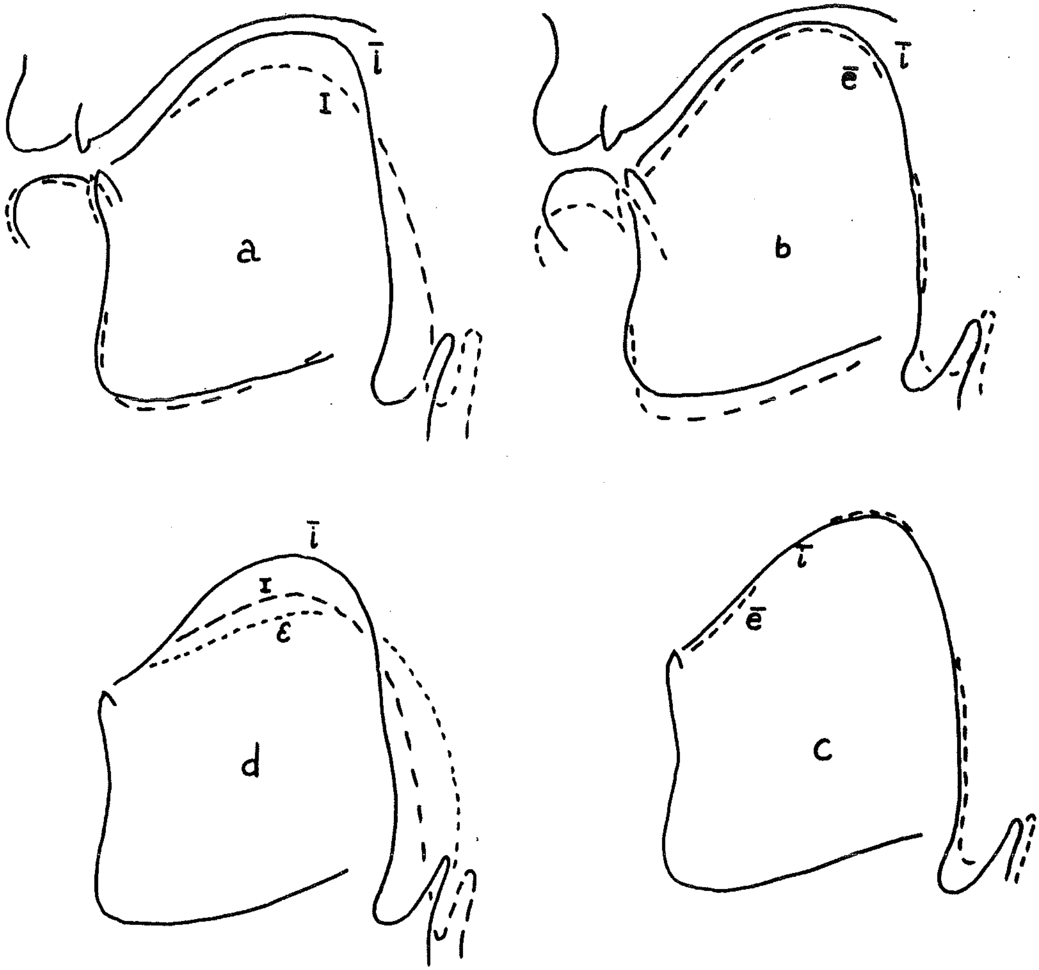

Fig. 3. Tongue height, jaw position and tongue shapes in German /ī, ɪ , ē, ɛ / from Chiba and Kajiyama's (1941) X-ray tracings.

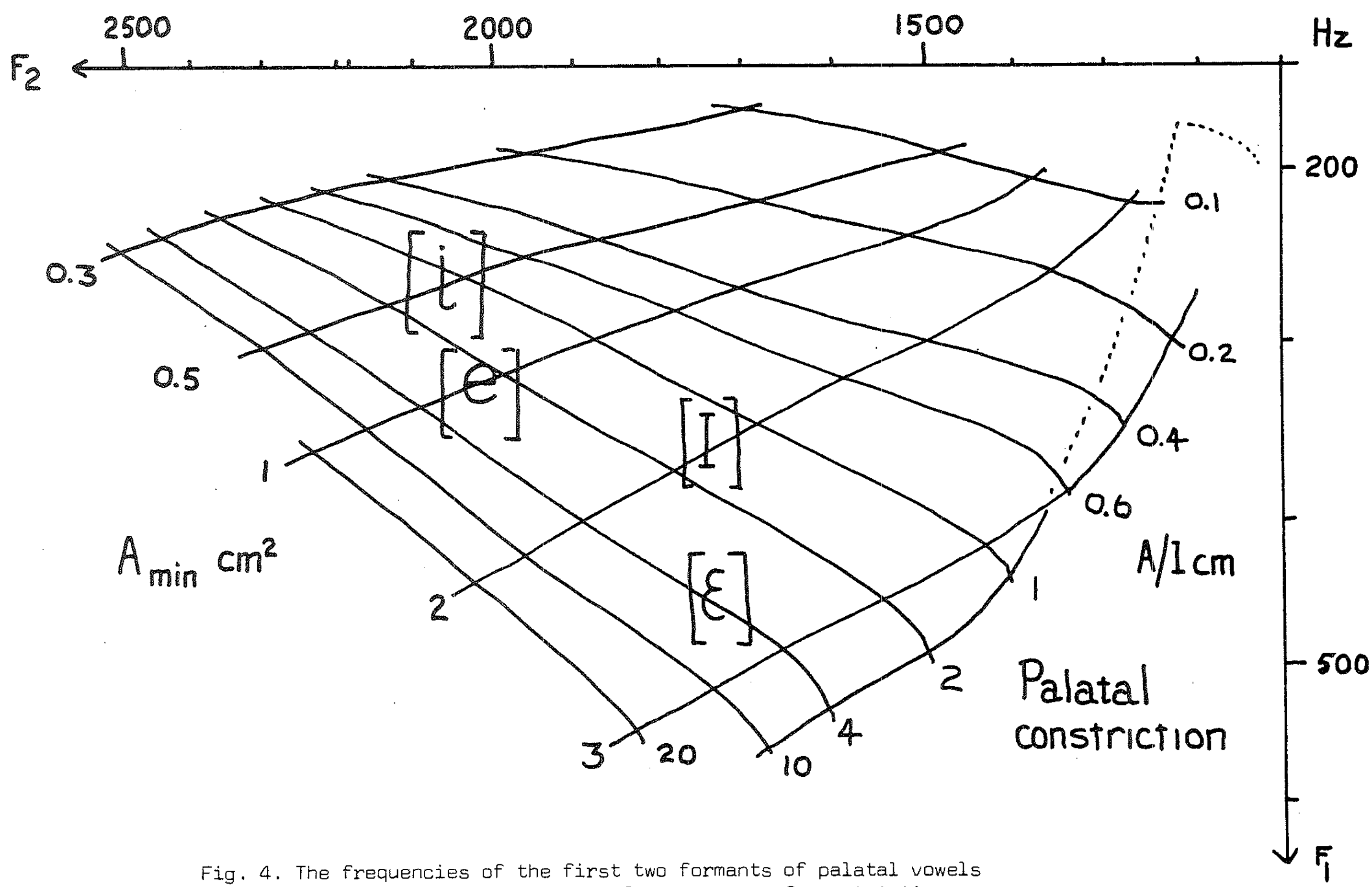

Fig. 4. The frequencies of the first two formants of palatal vowels for different combinations of the degree of constriction (A_{min} cm^2) and opening area/length ratio (A/1 cm). Based on Stevens and House's (1955) nomograms, for d_o = 12 cm.

show that the tongue was lower relative to the mandible for /ɪ/ than for /ī/, but that the jaws and lips were very similar.[3] Consequently, the mouth-opening was much the same for both vowels, but the constricted palatal passage was much wider for /ɪ/ and the pharynx much narrower. Reference to published nomograms such as those given by Stevens and House (1955) or Fant (1960) show that widening the palatal constriction from about 0.5 cm^2 for [i] to about 2.0 cm^2 for [ɪ], but keeping the same degree of mouth-opening, yields precisely the spectral difference between these vowels including the F2 difference of about 300 Hz. The Stevens and House nomograms have been redrawn at Fig. 4 for the palatal vowels[5]. The tracings at Fig. 3 do not indicate any tongue-arch retraction for /ɪ/, only lowering. Any of the [i] configurations at Figs. 1 and 2 can be transformed to an [ɪ] configuration by doubling the cross-section area of the palatal constriction from about 0.5 - 1.0 cm^2 to about 1.5 - 2.0 cm^2 while leaving the mouth-opening (jaw and lips) the same. The speaker does this by lowering the tongue about 3 mm with reference to the mandible. At the same time, lowering the tongue within the mandible causes the root of the tongue to narrow the lower pharynx. Both of these modifications, varying the degree of constriction at the hard palate and the volume of the lower pharynx, are relevant for the resonances of the vocal tract for these two vowels. Had the tongue been retracted instead of lowered, the constriction would have had to be withdrawn by as much as 2 cms to make F2 fall by 300 or 400 Hz, i.e. almost to the palatovelar location of [u]-like vowels. Stevens (1972) has pointed out that the plain palatal vowels are particularly insensitive to small variations of constriction location. It is just not acoustically profitable to make small tongue retractions for the palatal vowels. On the other hand, the nomograms show that very small variations of the degree of constriction yield relatively large spectral differences. Gunnilstam (1974) has underlined the role of varying the degree of constriction for producing large spectral differences.

I have also considered the traditional belief that the tongue arch is retracted slightly for rounded palatal vowels. Fig. 2 shows a selection of [i] and [y] tongue arches, none of which indicates such retraction. On the other hand they all show the tongue to be slightly lower for [y], irrespective of language. This difference can be entirely attributed to the mandible being slightly lower for the [y] renderings, the

[i] and [y] tongue profiles coinciding completely with reference to the mandible. Stevens's argument implies that tongue retraction for [y] would not contribute much to the spectral difference between [i] and [y], especially in comparison with the large spectral difference already obtained by rounding and protruding the lips.

There is one case where it is relevant to refer to gradual advancement or retraction of the tongue. This is for the difference between [ɑ, a, ,æ]-like vowels. The graver the low pharyngeal vowel, the further the tongue root is drawn into the lower pharynx to make the constriction even narrower. This is in fact the same parameter as for [i, ɪ], namely the degree of constriction at the narrowest part of the vocal tract. Owing to the 90^{o} bend in the vocal tract, this parameter is varied by raising or lowering the tongue for the palatal constrictions but by advancing or retracting the tongue for pharyngeal constrictions. Carmody found the tongue positions of Holbook's two examples of American English /ʌ/ very variable, one falling right outside the tongue arch polygon, "behind o". These two cases are illustrated at Fig. 5 (b, c). The "lowest" vowel of all for subject Z was /o/ while the "position" of /ʌ/ was identical with /æ/. For H, the "position" of /ʌ/ was "higher" and "further back" than /ɔ/ (right behind /o/ as Carmody observed). Carmody hoped that this puzzling situation could be resolved by examining more radiographs. However, I shall demonstrate that these cases are only bewildering in relation to the tongue-arching model. The very same pair of X-ray sets can be given a very different interpretation that finds both examples very similar and typical not only for these vowels but for [a]-like vowels generally.

The area functions at Fig. 6 (a, b) show that the resonator configurations in both sets were very similar. All three vowels expressing /ɑ, ʌ, æ/ had the same low pharyngeal place of constriction at about 5 cms above the glottis. The main difference was in the degree of constriction, narrowest for /ɑ/ and widest for /æ/:

	/ɑ/	/ʌ/	/æ/
cross-section area at constriction	0.5 - 1.0 cm^2	1.5 - 2.0 cm^2	2.5 - 3.0 cm^2

This can be compared with the area functions of French /ɑ, a/ renderings at Fig. 6 (d), where /ɑ/ has a constriction of about 0.8 cm^2 and

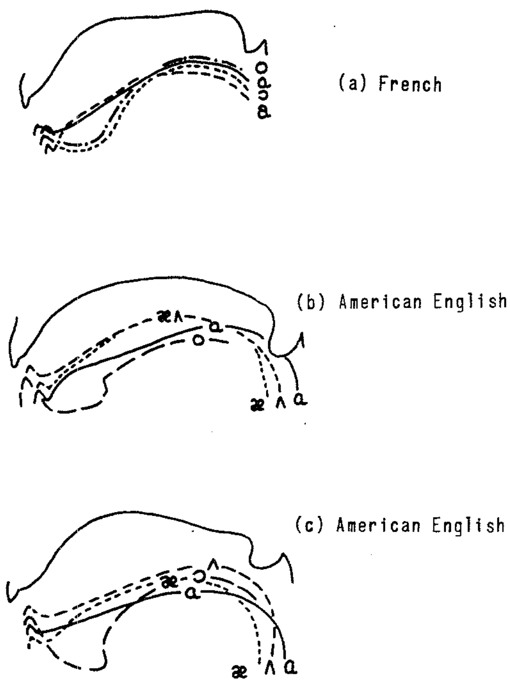

Fig. 5. Some confusing tongue heights: (a) mid and low back French vowels, and (b, c) English /ʌ/ related to some neighbouring vowels.

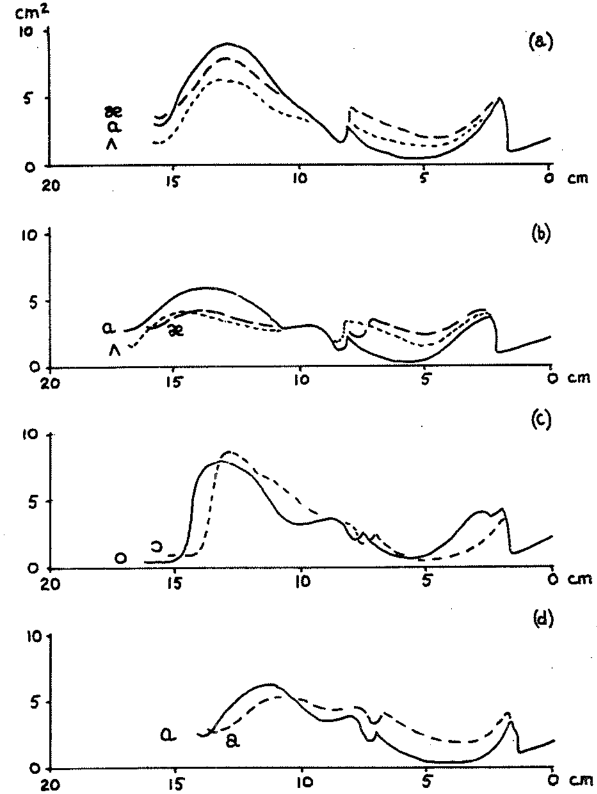

Fig. 6. (a, b) Area functions of the English vowels at Fig. 5 (b, c), and (c, d) area functions of the French vowels at Fig. 5(a).

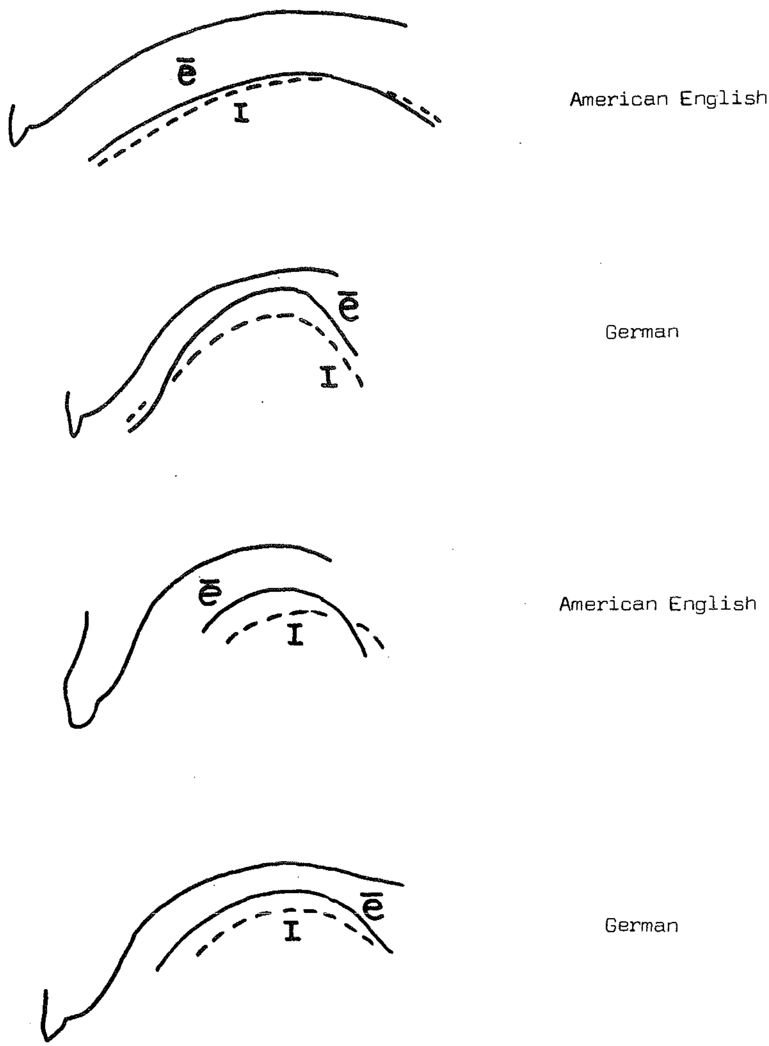

Fig. 7. Four cases of lax [ɪ] with lower tongue height than tense [ē].

/a/ about 2.0 cm^2. Clearly, the graver the [a]-like vowel, the narrower its pharyngeal constriction. The same conclusion for French [a]-like vowels was made by Mettas et al. (1971) after deducing the probable articulations for their observed spectra by referring them to Fant's nomograms. It has frequently been suggested that English /ʌ/ has an [a]-like quality, especially in Southern British English. But also Peterson and Barney's (1952) 76 American informants (men, women and children) all produced /ɑ, ʌ, æ/ with the highest first formant frequencies of all vowels (at least 600 Hz) and differentiated between them with the second formant frequency in three separate ranges between 1000 and 2000 Hz. The average F1 and F2 frequencies for the 33 men in that group were:

	/ɑ/	/ʌ/	/æ/
F1 (Hz)	730	640	660
F2 (Hz)	1030	1190	1720

These Peterson and Barney /ʌ/ spectra are certainly [a]-like.[6]

By comparing the vocal tract configurations of these vowels, and especially the place and degree of constriction, I have shown that Carmody's supposedly variable and inconclusive /ʌ/ renderings were in fact very similar and had the same resonator characteristics. This example, together with the comparison with the French [ɑ - a]-like vowels from one of Holbrook's French sets confirms the relevance of tongue body advancement and retraction for [ɑ, a, æ]-like vowels. But the relevant factor for shaping the resonating cavities is not the tongue arch position but the width of the constricted lower pharynx.

Tongue height

Meyer's and Russel's criticisms had mainly concerned tongue height, especially that the tongue was lower for [ɪ] than for [e] and lower for [ɔ] than for [a]. In addition my collected material also contained examples of [o] lower than [a] and confusion of the heights of [ʊ] and [o].

[ɪ] - [e]

This case arises in languages with quality contrasts /i - ɪ, e - ɛ/. In the X-ray sets I have collected, this applies for American English, and German. Southern British English dialects have quality contrasts for three of the monophthongs /i – ɪ – ɛ/ but a diphthong monophthong contrast /ɛj – ɛ/ is used for raid–red. Swedish has mainly quantity contrasts among the plain palatal vowels /i: – i, e:, ɛ: – ɛ/ (Elert, 1964) while other pairs of vowels may also have quality differences (Hadding-Koch and Abrahamson, 1966). There is general agreement that there is a quantity contrast for Swedish /i: – i/ with little quality difference, although there may be some variation between dialects.

Four examples from American English and German are illustrated at Fig. 7. All showing higher tongue arch for /ē/ than for /ɪ/. In all 7 possible sets for these languages, /ē/ was "higher" than /ɪ/ (other sets from these languages did not contain examples of both vowels). The higher tongue arch for /ē/ than for /ɪ/ was also reported for 5 out of 6 subjects by Ladefoged et al. (1972b) in a cineradiographic study of American English speech.

An early criticism of this observed "height inversion" was that tongue articulation was distorted by the use of chains for emphasizing the tongue outline or by the unnaturally sustained or repeated renderings of vowels necessitated by long exposure times, but the same result is still found when presentday cineradiographic techniques are used. The outlines of soft tissues are nowadays enhanced by applying a bismuth or barium compound to the articulators, and electronic intensification of the image makes possible very brief exposure times (50 to 200 frames/sec with only a few milliseconds radiation per frame).

Strenger's Swedish profiles show a higher tongue for short /i/ than for long /e:/ but this is to be expected if the subject had the non-qualitative /i: – i/ quantity contrast, so that this case is not necessarily an exception to the reported anomaly. On the other hand, Meyer's plastopalatograms from a Swedish subject (1910) had shown /e:/ to be higher.

The failure of the tongue-arching model to get the heights of [ɪ] and [e] right could of course be looked upon as an easily rectifiable mistake. These vowels need only be put in their correct places. But then the affinity of [i] with [ɪ] and of [e] with [ɛ] would be lost (Jespersen's objection). In either case, the model would still fail to capture the true articulatory relationship between "tense" and "lax" palatal vowels. I shall refer once again to the German example at

Fig. 3 to demonstrate how it is possible for "half-close tense" [e] to be "higher" than "close lax" [ɪ].[3]

Fig. 3 (a) shows only very slight mandibular difference between /ī/ and /ɪ/ and virtually the same lip separation, which means that the mouth-opening and hence the radiation were much the same for both renderings. The main difference between them is that the tongue is considerably lower for /ɪ/ than for /ī/, widening the palatal constriction and bulging into the pharyngeal cavity.

Fig. 3 (b) shows that the mandible was lowered much more for /ē/ than for /ī/ while the palatal passage was only slightly widened and there was consequently only a little bulging movement back into the pharynx. In fact, /ī/ and /ē/ have very nearly the same "tongue height", similar to what Kruisinger (1925) had noted on Meyer's radiograms.

Fig. 3 (c) shows that /ī/ and /ē/ had the same tongue shape relative to the mandible. Fig. 3 (d) shows that /ɪ/ and /ɛ/ had the same tongue shape relative to the mandible, both decidedly lower than for /ī, ē/.

The "tense" vowels /ī, ē/ were thus differentiated from the "lax" vowels /ɪ, ɛ/ by the height of the tongue within the mandible, while the "close" vowels /ī, ɪ/ were differentiated from the "open" vowels /ē, ɛ/ by the degree of mandibular depression. The component gestures shaping the vocal tract for these vowels are thus as follows:

PALATAL VOWELS:

		TONGUE IN JAW	
		HIGHER	LOWER
JAW	HIGHER	i	ɪ
	LOWER	e	ɛ

In the terms of the tongue-arching model, the tongue is "more central" for "lax" vowels than for "tense" vowels. Jakobson and Halle (1964) quote several examples expressing this view and conclude "tense phonemes are produced with more deviation from the neutral, central position than the corresponding lax phonemes". For a case similar to that described above, the English /ī – ɪ/ opposition, D. Jones (1967: § 160) wrote that the tongue was "lowered" and "retracted" for /ɪ/ with respect to /i/. Fig. 3 confirms the lower tongue but it does not support the notion of retraction. The relevant difference is in the respective mandibular and lingual components as outlined above, which in turn determine the degree of mouth-opening, the degree of palatal constriction and the size of the pharyngeal cavity.

Fig. 3 shows how the mandibular and lingual movements combine in opposite directions for /ɪ/ and /ē/ (high jaw and low tongue versus low jaw and high tongue respectively). The difference is sufficient for /ē/ to come out "higher" than /ɪ/, a simple explanation for what has hitherto appeared to be a perplexing anomaly in the terms of the tongue-arching model.

When these articulations are referred to the Stevens and House nomograms (Fig. 4), basing the parameter values on the vocal tract area function for each vowel[5], the following approximate frequencies are found for the first two formants:

	F1	F2
/ī/	250 - 300 Hz	2000 - 2100 Hz
/ē/	300 - 350 Hz	1950 - 2050 Hz
/ɪ/	325 - 375 Hz	1700 - 1800 Hz
/ɛ/	425 - 475 Hz	1650 - 1750 Hz

These are not far from what we might expect to find on spectrograms of adult male speech.

The result of the mandibular change from /ī/ to /ē/ (doubling the mouth-opening and widening the constricted palatal passage a little) appears mainly to result in a rise in F1 while F2 falls only slightly. The result of the lingual change from /ī/ to /ɪ/ (leaving the mouth-opening unchanged but widening the constricted palatal passage) is a simultaneous raising of F1 and lowering of F2. In the latter case the spectrum is "centralized" towards 500, 1500, 2500 ... etc. Hz, but without corresponding articulatory "centralization".

The separate mandibular and lingual differences between /ī/ - /ē/ and /ī/ - /ɪ/ respectively are thus compatible with the spectral character of these vowels. I realize that nothing has been proved by describing one example, although it is typical of the whole material. I have demonstrated that a pair of tongue heights that have been puzzling in traditional terms can be given an interpretation that is intimately related to the physiology and acoustics of vowel production, an impossibility within the framework of the tongue-arching model.

Ladefoged et al. (1972a) are sceptical of the type of solution outlined above, on the basis of their factor analysis of forces presumed to be acting on tongue shape (or, more precisely, the displacement of specified points along the dorsum of the tongue). They found individuality between six subjects in the way they utilized and coordinated mandibular and lingual movement. However, they record that three of the six had "a very bunched, tense, shape of the tongue in <u>heed</u> and <u>hayed</u>, and a flatter, lax, shape in <u>hid</u>, <u>head</u> and <u>had</u>", which is the same as that illustrated at Fig. 3. I shall do no more here than underline that five of their six subjects had /ē/ higher than /ɪ/ and that three of the six agreed with the case described above regarding different lingual gestures for "tense" and "lax" vowels, while the remaining three subjects disagreed both with that pattern and with each other[7].

[ɔ] - [ɑ, a] and [o] - [ɑ, a]

The second situation, conflicting tongue heights for [ɔ] and [ɑ, a] is expected to occur where there are two qualitatively different [o]-like sounds, whether the difference is distinctive (as in English) or allophonic (as in Spanish). It is the "lower" vowel [ɔ] that has been reported with tongue arch lower than for [a]. Fig. 8 shows two examples of [ɔ] lower than [a] or [ɑ], 4 examples of [o] lower than [a, ɑ] (unexpected) and 2 examples with both [o - ɔ] lower than [ɑ, a], one of them with [o] lower than [ɔ] (quite unforeseen and in complete contradiction to the tongue-arching model). The relative "heights" of these vowels in all the sets collected from the literature are compared at Fig. 9. Of the 22 sets where this comparison was possible, 8 had [ɔ] higher than [ɑ, a], 8 about the same height and 6 lower. In only one third of the possible sets was [ɔ] definitely higher than [ɑ, a] in accordance with the model. In addition, 6 had [o] lower than [ɑ, a] and 6 almost the same as [ɑ, a]. In two thirds of the possible sets, [o] was higher than [ɑ, a] in accordance with the model.

Notwithstanding the random character of the tongue "heights" of [o]-like and [a]-like vowels, it is interesting to discover that when the area functions for these vowels are compared, the rounded [o - ɔ]-like

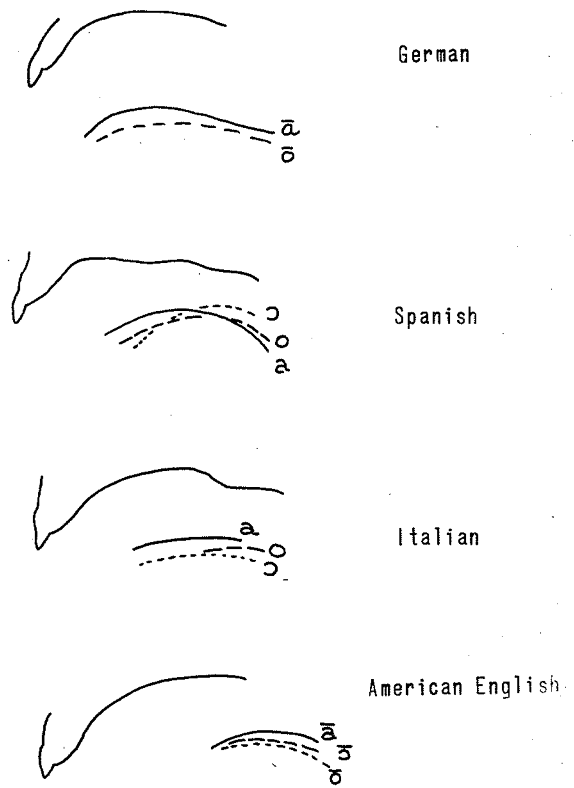

Fig. 8. Four cases of confused tongue heights of mid and low back vowels.

Relative tongue heights, [o,ɔ]-like and [ɑ, a]-like vowels

	[ɔ] higher than [ɑ, a]	[ɔ] same as [ɑ, a]	[ɔ] lower than [ɑ, a]	[o] same as [ɑ, a]	[o] lower than [ɑ, a]
Czeck	1			1	
English (Am)[8]	1	1	1		1
English (S Br)[8]	1	1			
French		3	1		
German	2		1		1
Icelandic	1				
Italian			1		1
Japanese					1
Korean	1			1	
Polish			1		
Portuguese		1			
Russian			1	2	1
Spanish		2		1	1
Swedish	1			1	
	8	8	6	6	6
Total compared		22		34	

Fig. 9. Comparison of tongue heights of [o, ɔ] -like vowels from a large number of sets of published X-ray tracings.

vowels always have a place of constriction a little farther from larynx than the [ɑ - a]-like vowels. I shall illustrate one case, Holbrook's French subject C (female). Fig. 5 (a) shows that the tongue "heights" for her "back" vowels were ranked [o, ɑ, ɔ, a] from "higher" to "lower". Fig. 6 (c, d) shows that the /o/ and /ɔ/ renderings constricted the pharynx at a distance between 5 and 6 cms above the glottis, while the /ɑ/ and /a/ renderings constricted the pharynx between 4 and 5 cms above the glottis. Whatever the orders of tongue heights in sets of vowels, examination of all the sets indicates that this relation of constriction locations for the two types of vowel is a very strong constant of speech[3].

[ʊ] - [o]

I also found several instances of [ʊ] lower than [o]. The only languages where this might be expected are those with clear quality contrasts for /ū - ʊ/, that is, English and German in this material. There were 7 sets containing the [ʊ - o] pair among the 38. Of these, 3 had [ʊ] higher than [o] (1 German, 1 American English, 1 British English), 1 the same (1 German) and 3 with [ʊ] lower than [o] (1 German, 1 American English, 1 British English). This suggests the distribution for this pair is random rather than language specific.

THE WEAKNESSES OF THE TONGUE-ARCHING MODEL

The comparison of published X-ray tracings in the preceding section confirms the anomalous tongue positions that were said to contradict the tongue-arching model. "Close" [ɪ] is more "open" than "half-close" [e]. The "heights" of "half-open" [ɔ] and "open" [a] are random. In only two-thirds of the cases was the tongue "higher" for "half-close" [o] than for "open" [a]. The concept of gradual retraction is without foundation. Tongue arch position in terms of "height" and "retraction" is ambiguous with regard to resonator shaping and consequently to the spectrum of the vowel generated in the vocal tract. The vocal tract configuration is dependent on a number of other factors, information on which is not generally available in vowel descriptions based on the tongue-arching model since they are external to it and customarily disregarded. The advantage of the tongue-arching model was that it had seemed to offer 19th century phoneticians better possibilities for describing finer shades of vowel quality than could be generated by the ancient model it displaced. Its weaknesses are related to the fact that it was a product of the imagination that was never confirmed in serious tests. It is physiologically unsound since it was based on a misconceived notion of tongue articulation for vowels. Consequently it fails to predict the values of its parameters correctly for many vowels. The ambiguity of the relationship between the values of its parameters, physiological activity, resonator configuration and spectral output means that it is powerless to explain central areas of speech production.

Physiological weaknesses

There are two serious physiological weaknesses.

Firstly, the model neglects the pharynx completely. The earliest radiograms had shown the low pharyngeal constriction for [a]-like vowels, and its significance was underlined by Russel. Carmody (1941) made a detailed analysis of the pharyngeal cavity from Holbrook's radiograms, but he did not try to relate his findings to the tongue-arching model, in which he remained a firm believer. More recently, the pharyngeal cavity has been explored by tomography (Fant, 1960, 1964) and ultrasound (Minifie et al. 1970). Delattre (1971) has studied pharyngeal articulations with cineradiography. Ladefoged et al. (1971) have made casts of the living pharynx and Lindqvist and Sundberg (1971) have inspected the pharynx with a fibrescope. The shaping and acoustical significance of the pharyngeal cavity are outside the domain of the tongue-arching model. although the tongue root position proposal (Stewart 1967, Halle and Stevens 1969, Perkell 1971, Lindau et al. 1972) is an attempt to relate the difference between tense and lax vowels to the volume of the lower pharynx. The meaning of such supplementary concepts as "uvularization" and "pharyngealization" is not clear. The extrinsic muscles of the tongue (which are generally held to be mainly responsible for tongue shape and position in vowels) all contract in the pharyngeal region and whatever task these muscles may otherwise be performing they always immediately and directly alter the pharyngeal cavity. Three pairs of muscles contract in the lower or mid pharyngeal region - the hyoglossi, the posterior genioglossi and the glossopharyngei. The fourth pair, the styloglossi, contract across the upper pharynx. Nothing of this is captured by the tongue-arching model, despite its supposedly physiological basis.

The second major physiological weakness is that the location of the tongue arch cannot readily be related to knowledge of the state of the tongue muscles. The ancients had only been hampered by their insufficient knowledge. The celebrated Persian physician and philospher Ibn Sīnā (1000), better known to mediaevel Europeans as Avicenna, had made a detailed description of the muscular structure of the tongue, but had to admit failure in his attempt to relate it to tongue movement during vowels. This was probably due to the fact that either he, or Galen whom he may have been quoting, had dissected the tongue of the ape and not that of man (Singer, 1957: p. 53)[9]. But since at least the treatise of Hellwag (1781)[10], there has been virtual agreement about the role of the extrinsic muscles of the tongue for directing lingual gestures to form constrictions in the vocal tract. The presentday view is given by, for example, MacNeilage and Sholes (1964), Zemlin (1968: p. 281), Harris (1971), Raphael (1971a, 1971b), Smith (1971). The hyoglossi draw the tongue bodily downwards to narrow the lower pharynx. The posterior genioglossi pull the tongue root forward to widen the pharynx and assist in raising the body of the tongue towards the palate. The glossopharyngei (fibres of the pharyngeal constrictors that insert into the sides of the tongue) draw the tongue back into the mid-pharynx. The styloglossi draw the tongue upwards and rearwards towards the soft palate. The effect of contracting these muscles, alone or in combination, is to narrow different regions of the vocal tract, controlling the location of the constriction and the volumes of the cavities. The amount of contraction, together with the movement of the mandible, controls the degree of constriction. A type of model based on constriction location is compatible with observable motor activity. But specific muscular activity is not unambiguously and exclusively related to the raising or lowering, advancement or retraction of the tongue-arch, so that the tongue-arching model constitutes a very weak link between neuromotor activity and articulation. This means it provides a bewildering articulatory framework, not least for electromyographic investigations of tongue movement.

Predictive capability

One aspect of the weak predictive capability of the tongue-arching model has already been described. The tongue positions that can be observed in speech are not always the same as those prescribed by the model. The analysis of Carmody's difficulties with "low back" vowels and the English /ʌ/ profiles showed that while the coordinates defining "tongue position" are largely irrelevant for the articulation of vowels, a type of model based on the vocal tract configuration did not find these profiles in any way enigmatic. It would not therefore be sufficient simply to rectify the location of the errant vowels in the polygon by assigning the "correct" coordinates. It would still be impossible to predict the resonator configuration satisfactorily, and hence the spectrum, from the coordinates. It would similarly remain impossible to predict the underlying motor activity.

Explanatory power

In view of its unsound physiological foundation and ambiguous relation to vocal tract shaping and resonance properties, and its consequently unsatisfactory predictive capability, the tongue-arching model failed to provide a smooth and direct link between articulation and acoustics. It could not therefore explain the relationships between the successive links of the speech chain, the systematic preferences for the structure of vowel systems, the phonetic processes involved in sound changes and so on. It is not surprising that the esteem of articulation fell when compared with the progress made in speech acoustics. Advances in the analysis of the acoustic structure of speech and in psycholinguistics have made it possible to elucidate much of the role played by acoustic cues in perception. Acoustic contrast has been accorded a firm position in speech theory[11]. But the bewildering relationship between the parameter values of the tongue-arching model and the spectral character of vowels has prevented the construction of a comprehensive view embracing and integrating all phases of vowel production.

AN ALTERNATIVE ARTICULATORY MODEL

Spectrographic analysis over the past few decades has demonstrated that the spectral character of vowels is relatively constant, especially for the same speaker (for example, Joos, 1948; Potter and Steinberg, 1950; Peterson and Barney, 1952) confirming the isolated examples of spectral analysis published in previous years (Malmberg, 1952: pp 89-97). Differences of formant frequency range between speakers due to differences of vocal tract scale are regular and predictable. Spectral variations within the same spaker's speech are regular and can be related to such factors as consonant environment, degree of stress, style or temporal constraints (Tiffany, 1959; Stevens and House, 1963; Lindblom, 1963). The relative spectral contrasts utilized for phonemic distinctions are universal (Jakobson et al. 1952). Contrasting this spectral constancy with the apparent variability and confusion of tongue articulation and knowing that there is theoretically an infinite number of possible resonator shapes for a given spectrum, it was natural that many phoneticians preferred to believe that there was no constancy at all in articulation and that the speaker's only concern was to produce the correct spectrum. For example, Malmberg (1952:99) has written "on peut changer un [e] en un [ø] en arrondissant les lèvres. Mais on peut produire à peu près le même effet en retirant un peu la langue. Les deux procédés amènent un abaissement du formant haut de la voyelle ... C'est par cette différence dans la structure acoustique, et non pas par la position des organes, que le [ø] se distingue du [e]".

However, the examples discussed indicate that the speaker is nevertheless striving to create a constant vocal tract configuration for a given vowel, thereby confirming constancy in two adjacent links of the speech chain - resonator shape as well as spectrum. Irrespective of language, the [o - ɔ]-like vowels always have a tongue constriction a little higher in the pharynx than the [ɑ - a]-like vowels. Similarly, all [ɑ - a - æ]-like vowels are produced by constricting the lower pharynx, the degree of gravity being related to the degree of constriction.[3] If the speaker is, as it seems, always striving to produce one constant configuration for a vowel, then it is also reasonable to look for constancy in the manner of forming these configurations. Is there, for example, a simple set of underlying gestures that are combined in various ways to achieve the desired configurations? The preceding discussion concerning the "tense-lax" palatal vowels [i, ɪ, e, ɛ] indicated that mandibular and lingual gestures are combined in different ways for these vowels. Further, the similarity of the [i, ɛ, y] profiles compared at Figs. 1 and 2 adds further strength to the notion that these speakers have produced comparable cavity configurations by using the same means.

There has been a growing tendency in recent years to look in this direction for a substitute articulatory model. Stevens and House (1955) found that "X-ray studies indicate that during the articulation of vowels the dimensions along the vocal tract are controlled primarily by the position of the tongue constriction and by the degree of constriction". Kaneko (1957) has compared the American English and Japanese vowel systems with reference to the vocal tract configurations. Lindblom and Sundberg have described the Swedish vowel system (1969a) and the cardinal vowels (1969b) using the place and degree of constriction to define the place of articulation. I have myself described the West Greenlandic vowel system (1971) using the place of constriction as a phonological feature that can be used in generative rules[3]. Pétursson (1974) has described the Icelandic vowels with reference to the constriction location. Lindblom and Sundberg (1971), simulating physiological factors that determine the vocal tract area function, have explored and described the spectral consequences of individual mandible, tongue and lip movements. Stevens and House (1955) noted the controversy regarding articulation and vowel diagrams, but did not wish at that moment to suggest "that the present data validate any theory of static positions for vowel production". However, the preceding discussion concerning palatal and pharyngeal vowels indicated that the place and degree of constriction describe more relevant and constant differences between vowel articulations than did the parameters of the tongue-arching model. The features of cavity configuration, and their manner of formation can provide the basis for an alternative description of vowel articulation, as a substitute for the tongue-arching model.

SOME IMPLICATIONS FOR PHONOLOGY

The difficulties arising from the irrelevancies of the tongue-arching model for vocal tract shaping are acutely felt today when so many phoneticians wish to model the vocal tract and simultaneously discuss the articulation, acoustics and phonological relationships of vowels, or ponder the suitability and phonetic meaning of phonological features (for example Ladefoged 1964; Lindblom and Sundberg 1969a, 1969b, 1971; Perkel 1971; Lieberman and Crelin 1971; Ladefoged et al. 1971a, 1972b; Lindau et al. 1972; Lindblom 1972; Stevens 1972).

Phoneticians of the acoustical school, recognizing the fallacies of the tongue-arching model, had aimed instead to use the spectral characteristics of speech segments as descriptors and features when analysing phonemic systems or when dealing with problems of phonology. The best known scheme of this kind was that of Jakobson et al. This was repeated by Halle (1964) and Jakobson and Halle (1968), and was widely used for nearly two decades. But the acoustically oriented basis has given way to articulation again, while the function of features has undergone revision. In particular, McCawley (1967) pointed out certain inadequacies arising from the different roles played by feature systems in Preliminaries to Speech Analysis and in Halle's Sound Pattern of Russian of 1959. Jakobson had amphasized the contrastive function of the features for denoting phonemic distinctions, whereas Halle was using the features for the complete systematic specification of segments necessary for the ordered rules of a generative phonology. McCawley found that Jakobson's desire for the set to be minimal, achieved for example by subsuming the spectral characteristics of both lip-rounding and pharyngealization under the one feature flat, meant that the set was too small for a generative phonologist and made it impossible for him to distinguish the very different processes involved in for example labial and pharyngeal assimilations. The enormous expansion of the set of features, the shift to articulation and the new role of features can be seen in Chomsky and Halle (1968: chapt. 7) where it is explained that "the totality of phonetic features can be said to represent the speech-producing capabilities of the human vocal apparatus".

Following the renewed focus on articulation, there is a grave risk that the tongue-arching model will become even more firmly entrenched. Chomsky and Halle's three features - high, low, back - denote six positions of the tongue body (no longer the tongue arch) and indicate that the tongue is raised, lowered or retracted from an arbitrary origin, the position for [ɛ][12]. This small set of features avoids the erroneous gradual retraction concept of the tongue-arching model proper. It is possible to translate the feature specifications of the small primary set of vowels generated by this framework into vocal cavity configurations, although the procedure is complex. This can be done because the underlying arrangement of the vowel scheme bears a closer affinity to the ancient pharynx-velum-palate-apperture typer of model (which reflects cavity configuration) than to the tongue-arching model. Phoneticians in the 19th century occasionally split the pharyngeal

[a]-like vowels and divided them between the palatal and labiovelar series, thus:

PHARYNGEAL

	ɑ	a	
	o	e	
LABIOVELAR	u	i	PALATAL

back

From this follows the fact that the only unique relation between the parameters of the two arrangements is that *low* vowels have a low pharyngeal constriction and *non-low* vowels do not.

The six vowels are as follows (including the redundant labialization of *non-low* back vowels [u, o]):

	ɑ	a	i	ɛ	u	o	
high	–	–	+	–	+	–	
back	+	–	–	–	+	+	(I)
low	+	+	–	–	–	–	
labial	–	–	–	–	+	+	

The discarded information about vocal tract configurations can be filled in from general phonetic knowledge of the articulation of this small set of very frequent vowels. One possible arrangement is as follows:

(i) *Constriction location*: [i, ɛ] have palatal constrictions, [u] a palatovelar constriction, [o] a pharyngovelar constriction and [ɑ, a] a low pharyngeal constriction.

(ii) *Degree of narrowing*: [ɛ, a] have wider constrictions, [i, u, o, ɑ] have narrower constrictions.

(iii) *Mouth-opening*: [ɛ, o] have wider mouth-openings relative to [i, u] respectively, and [ɑ, a] have wide openings.

(iv) *Lip-rounding*: [u, o] are labial

From this information, a new matrix can be constructed (where the features *palatal*, *velar*, *pharyngeal* define constriction locations):

	ɑ	a	i	ɛ	u	o
palatal	−	−	+	+	+	−
velar	−	−	−	−	+	+
pharyngeal	+	+	−	−	−	+
narrow	+	−	+	−	+	+
labial	−	−	−	−	+	+
open	+	+	−	+	−	+

(II)

There is no reciprocal one-to-one relation between the features and values of (I) and those of (II), except that low vowels have their constriction low in the pharynx. High vowels [i, u] are non-pharyngeal, but it does not follow that non-high vowels are pharyngeal ([ɛ] is palatal). Not all back vowels are non-palatal ([u] has a palatovelar constriction), nor are all non-back vowels palatal ([a] has a pharyngeal constriction).

The features and values of matrix (I) can be transformed to those of matrix (II) by a conditional statement such as (III):

$$
[\beta\,\text{high}] \longrightarrow
\left\langle
\begin{array}{ll}
\beta & \left\langle \begin{bmatrix} +\text{palatal} \\ \alpha\,\text{velar} \\ -\text{pharyngeal} \\ -\text{open} \\ +\text{narrow} \end{bmatrix} \right\rangle \;/\; \left\langle \begin{bmatrix} \overline{} \\ \alpha\,\text{back} \end{bmatrix} \right\rangle \quad \text{(IIIa)} \\
-\beta & \left\langle \begin{array}{ll} -\gamma & \left\langle \begin{bmatrix} -\alpha\,\text{palatal} \\ \alpha\,\text{velar} \\ \alpha\,\text{pharyngeal} \\ +\text{open} \\ \alpha\,\text{narrow} \end{bmatrix} \right\rangle \\ \gamma & \left\langle \begin{bmatrix} -\text{palatal} \\ -\text{velar} \\ +\text{pharyngeal} \\ +\text{open} \\ \alpha\,\text{narrow} \end{bmatrix} \right\rangle \end{array} \right\rangle \;/\; \left\langle \begin{bmatrix} \overline{} \\ \alpha\,\text{back} \\ \gamma\,\text{low} \end{bmatrix} \right\rangle \quad \begin{array}{l} \text{(IIIb)} \\ \\ \text{(IIIc)} \end{array}
\end{array}
\right.
$$

Chomsky and Halle's three tongue body features (I) can only provide 2 x 3 positions. If a need is felt for more position categories, extra features have to be provided – for example front and mid which will permit 3 x 4 tongue positions. An even more formidable statement than

(III) will be needed to derive vocal tract configurations, if it were at all possible still to do so. Worst of all, the addition of front would reintroduce the error of the central tongue position. Further, apart from the confusion and ombiguity of tongue height, there has never been agreement about the features needed to generate four degrees of opening for vowels[13]. The Chomsky-Halle arrangement does not therefore avoid the weaknesses of the tongue-arching model when treating vowel systems requiring more tongue positions than the basic six. They share the situation of the early 19th century users of the ancient type of model - the number of parameters available is insufficient to generate the number of vowel categories observed in more complex systems. Moreover, if every available possible feature combination is utilized to provide pigeon holes for difficult vowels, disregarding physiological and acoustic data, unrealistic solutions will result. This is the course resorted to by Chomsky and Halle when they pair off English /a/ and /ʌ/ with /ɔ/ and /o/ respectively as non-labial members of low and intermediate tongue height categories. It was demonstrated above that with regard to vocal tract shaping, English /ʌ , a/ share the lower pharyngeal constriction location, and /o, ɔ/ the higher pharyngovelar constriction location.

The translation of (I) into (II) by (III) seems to be a very clumsy necessity to have to go thorugh before the phonological component can yield its output in a form that is related to sound quality via spectral character and resonator configuration. Yet it is the ability of a model to relate phenomena at the separate links of the speech chain that sharpens the predictive capability and increases the explanatory power of a theory for phonology. Matrix (I) will generate 6 letters of a phonetic alphabet. If we stop there, the phonology output will be a phonetic transcription where each letter stands for a set of feature specifications. This was Chomsky and Halle's goal[14]. But the goal can be constrained even further, to make the phonological component deliver its output in a form compatible with current speech production theory. Fant (1969) has written: "Before we can accomplish the happy marriage between phonology and phonetics we have to work out the rules for predicting the speech event given the output of the phonological component of the grammar. To me this is the central, though much neglected, problem of phonetics."

It is well known that opinions differ between linguists as to whether or not generative rules have psychological reality. At least phoneticians can demand that when rules are written in a set of features that have an articulatory basis, the standard of physiological accuracy should be set high. Critics such as Fant (1969) and Vennemann and Ladefoged (1971) accept the linguist's need for abstract classificatory or "cover" features alongside strictly phonetic features. One can always imagine a feature interpreting component that will clothe the features of the phonology output with the appropriate phonetic character. Statement (III) above would be part of such a component. The problem is whether a feature interpreting component is always necessary, and if it is then what form it should have and where and how smoothly it should operate. With respect to the present specific issue, the movement of the tongue and the shaping of the vocal tract for vowels, I believe it would be more suitable to write the phonology straight away in features similar to those of (II) rather than switch terminology and conceptual framework halfway by translating the present features (I) into features shaping the vocal tract (II) with some heavy interpretive device such as (III).

Ladefoged (1970) in debate with Fromkin (1970) expressed the view that it would be unwise to try to claim for any current feature system "any more than that it is a summary of the data we know we now have available, and there are several limitations on our present data." Chomsky and Halle (p. 298) had themselves recognized that the many gaps in their knowledge made the success of their ambition to "cover every inherent phonetic feature" somewhat problematical. The set of features in which the phonological component is written is constantly under review and I believe that a revision as suggested above would be a valuable modification, bringing the phonetic apparatus of phonology more closely into line with current speech production theory and thereby increasing its explanatory power.

CONCLUSIONS

Cases had been reported of [ɪ] having a lower tongue height than [e], and [ɔ] lower than [ɑ], contradictory to the tongue heights prescribed by the tongue-arching model. My examination of all possible cases in

38 sets of X-ray tracings published during the past 70 years confirms these reports. In every example, [ɪ] was lower than [e]. The tongue height relation between [ɔ] and [ɑ - a] was random. Unexpectedly, some cases of [o] lower than [ɔ] were also found and even [o] lower than [ɑ]. In addition, a few cases suggested the relation between [ʊ] and [o] was also random. Further, the concept of a continuous scale of tongue retraction was found to be false. The tongue positions prescribed by the model do not agree with those observed in actual speech. This model therefore gives an inaccurate representation of vowel articulation.

The concept of tongue height is ambiguous with regard to vocal tract shaping. Its effect varies according to the location of the tongue constriction in the vocal tract. Its two components (mandibular and lingual) have different acoustic consequences, the former altering the radiation characteristics of the mouth-opening while the latter does not. This ambiguity means that tongue height is useless as an articulatory parameter of vocal tract shaping. Close comparison of one set of German /ī, ɪ , ē, ɛ/ profiles and area functions indicated that the mandibular and lingual components must be treated separately as independent gestures, the difference between [i, ɪ]-like and [e, ɛ]-like vowels being mandibular, and between "tense" and "lax" vowels lingual.

Vocal cavity configurations are constant for different renderings of the same vowels, although the X-rayed tongue arch positions may be as random as those observed for [ɔ]-like and [a]-like vowels. The same was true for a particularly puzzling pair of English /ʌ/ tongue arch positions that Carmody was unwilling to accept, but whose area functions were nevertheless remarkably similar. The variability of tongue arch position and the constancy of vocal tract configuration indicates that it would be more fruitful to describe how articulation strives to achieve the constant cavity configurations.

The <u>physiological basis</u>, the <u>predictive capability</u> and the <u>explanatory power</u> of the tongue-arching model are all very weak. It neglects the pharynx. The coordinates of tongue arch position (height and fronting) are not related to the observed activity of the extrinsic muscles of the tongue. The tongue arch positions it aims to describe are found to be very variable in actual speech and are largely irrelevant to the detailed shaping of the vocal cavities. Its parameters are ambiguous with regard to the acoustic output of the vocal tract. Consequently, the tongue-arching model is a poor articulatory medium for relating neuromotor activity, movements of the articulators, vocal tract configurations and the acoustic character of speech. It obstructs the building of a comprehensive description of speech production in which each of the successive stages (neuromotor, articulation, cavity shaping, acoustic output) are unambiguously related to each other. It therefore constitutes an unnecessarily weak link in phonetic and linguistics theory.

For several decades, there has seemed to be greater regularity in the spectral character of vowels than in their articulation in terms of the tongue-arching model, and many phoneticians have therefore preferred an acoustic or auditory rather than articulatory description of speech. However, it was seen above that this spectral constancy is matched by similar constancy in the vocal tract configurations. I suggest that articulation is not in itself inconstant, but that it has instead been described in terms of an unsatisfactory model whose parameter values have provided a bewildering and variable picture of actual speech. Given that the spectral character of speech and the cavity configurations are constant, there is probably similar constancy in the coordination of the gestures that create the resonating cavities and in the packages of motor commands necessary for these gestures.

A more suitable definition of the place of artculation of vowels would be in terms of the place and degree of tongue constriction. Now that the acoustics of the vocal tract are more thoroughly understood, there is a growing tendency to look in this direction for an alternative to the tongue-arching model. The explanatory power of the phonological component of grammar would be greatly enchanced if the features of tongue movement were based on this type of model instead of on the tongue-arching model.

NOTES

1. Except in general terms. For example the 6th or 5th century BC authors of the Sanskrit Atharva-Veda Prātiśākhyā recitation manual (Whitney, 1862: § I.i.36) taught that the short Sanskrit [a] for /a/ was "obscured" by narrowing the mouth-opening relative to the long [a:] for /a+a/. Another example can be found in a treatise of the 2nd century AD Roman grammarian Terentianus Maurus (Keil, vol. 6) who described how the "tragic tone of the mouth cavern" of [o] and the "graver quality" of [u] are produced by rounding and protruding the lips.

2. These additional branches were known as mixed because they combined the tongue of one basic series (palatal or velar) with the lips of the other (plain or round). The same term mixed later came to denote the "central" vowels of the tongue-arching model, whence the subsequent confusion in interpreting the older trees.

3. There are several references in this paper to conclusions based on the collection of published sets of X-ray tracings. More detailed accounts will be given in a forthcoming thesis. The four constriction locations were found in every published set examined. The jaw and tongue positions described for "tense" and "lax" palatal vowels are typical for the whole collection of X-ray tracings and for my own X-ray film of Southern British speech. The description of the W. Greenlandic vowel system has been fully revised and fresh cineradiographic material added. See also note 13.

4. Exceptions, where they were given prominence, were Kruisinga's textbook of English pronunciation, Jespersen's handbook and Russel's polemic treatise on vowel theory. Vietor had agreed with Meyer. D. Jones (1967: § 129) mentioned that "the late Dr. E. Meyer of Stockholm obtained excellent diagrams of the tongue positions of vowels by means of a row of fine leaden threads attached to an artificial palate" but did not report that these same excellent diagrams contradicted part of what he himself was teaching in the book. Malmberg has frequently pointed out how Meyer's findings, both in this and other fields, have been confirmed by later investigators. For example, in 1952 and in his obituary tribute to Meyer (1953) where he wrote of

"...seine plastographische Methode...wodurch er die der älteren Palatographie ersetzte und dank welcher er dann auch die althergebrachte Vorstellung von einer festen Beziehung zwischen Zungenstellung und Lautklang als principiell falsch ablehnen konnte", and "jedenfalls hat die moderne Phonetik durch eine Kombination von Röntgenographie und akustischer Lautspektrographie die Richtigkeit der Meyerschen Ergebnisse in erstaunender Weise bestätigt". It should be noted that my thesis is that Meyer discredited one particular tongue articulation model for vowels. I still maintain that there is a firm relationship between tongue gestures and vowel quality.

5. The Stevens and House nomograms give the frequencies of the first two formants generated by a three parameter vocal tract model for different constriction locations, for different mouth-openings (represented by the values of the lip-opening area/length ratio A/l cms) and for different cross-section areas at the constriction. When these numbers are inserted in their equation, a close approximation to a natural vocal tract area function is obtained. Fig. 4 gives the case where the constriction is located 12 cms from the source, a suitable value to represent the palatal vowels.

6. This comment applies only to the examples quoted here. There are differences between dialects. The quality of the vowel segment denoted /ʌ/ today has changed from an [u]-like quality over the past few hundred years, the older quality still being preserved in spellings. There are dialects, especially in northern and central England, where this change has only been partial, the corresponding vowel having an [ʊ] or [ɤ]-like quality. While handbooks of American English frequently quote an [ə]-like quality for /ʌ/, the Peterson and Barney spectra have the typical high F_1 of an [a]-like quality.

7. This disagreement prompted Ladefoged and his colleagues to conclude that each indvidual speaker evolves articulatory behaviour that is peculiar to himself.

8. For the English dialects, [ɔ] represents the vowel of caught in American English and cot in southern British English, while [o] represents the vowel of coat in American English and caught in southern British English.

9. Galen's own account of the structure, movements and innervation of the tongue is contained in books IX (cranium, brain and cranial nerves) and XI (face and jaws) of his "On the uses of the parts of the body of man" (Darembourg, 1854). It is hardly surprising that reference to apes was not helpful for this point. A necessary element of the ontogenesis of the speech organs (compared with the oral anatomy of the non-human primates) is the 90° bend in the vocal tract, resulting from the erect posture of man, that permits a wide range of variation of the vocal cavities by means of tongue movement. This has been particularly stressed by Lieberman (1972).

10. One of the principal anatomical references of Hellwag is to Albinus's edition (1744) of the plates of Eustachius that had remained unpublished from 1522 until 1714. They are considered to be more accurate than those of Eustachius's contemporary Vesalius (Singer, 1957, p. 135). For the tongue in particular, Hellwag referred to a work of Heuermann, De lingua humana, 1749.

11. But the doctrine of maximum auditory contrast will need to be modified. It is not true that acoustic contrasts are always as large as possible or that when the number of phonemes in a vowel system is increased the new contrasts are necessarily the largest available. Consider for example the simple observation that numerous qualitative distinctions may be evolved among the palatal vowels (as many as /i, ɪ, e, ɛ, y, ʏ, ø/ with consequently very small spectral contrasts) while the whole spectral range of [a]-like vowels frequently remains phonemically undivided. One rarely finds as many as three qualitatively different [a]-like phonemes (as in English, /æ, ʌ, ɑ/). This cannot be explained in terms of seeking out maximum contrasts. I shall argue in a forthcoming paper that there are good articulatory reasons for vowel systems to develop in this way. I can mention in particular the excellent tactile feedback afforded by the tongue in contact with the upper teeth and the opportunity for individual exploitation of mandibular and lingual gestures, permitting precise control of palatal vowels. For [a]-like vowels the mouth-opening must be wide (a close opening would endanger contrasts with [ɛ], [ɜ] and [ɔ]) and labial contrasts are not practical (lip-rounding might lead to confusion with [œ] and [ɔ]). This means that the only articulatory variable that can

be exploited for useful spectral contrasts among [a]-like vowels is the degree of tongue constriction in the lower pharynx. Here is the key to why the predictions of the magnetic repulsion analogy of Liljencrantz and Lindblom (1972) became weaker for systems of seven vowels or more. Instead of exploiting more constrasts among the palatal vowels, it preferred to arrange vowels equidistantly around the boundary of the spectral space.

12. Ladefoged has pointed out that their belief in this as a neutral tongue position is not well founded. They refer to what they call a preparatory position seen at the beginning of X-ray motion films. They may have been misled by a superficial similarity between the normal breathing configuration and the palatal [ɛ] configuration.

13. Suppose it is necessary to transform the three "heights" [i, ɛ, a] (+high -low, -high -low, -high +low) into four for [i, e, ɛ, a]. The introduction of a feature mid necessitates a redefinition of the other features to enable [ɛ] to become +low (+high -mid, +high +mid, +low +mid, +low -mid). Wang's suggestion (1968) for +high -mid, +high +mid, -high +mid and -high -mid also necessitates amendments to the initial set of features prior to the introduction of the fourth "height". I propose instead a set of articulatory features based on gestures that shape the vocal cavities. This will generate any relevant number of vowels along the [i - ɑ] scale as follows:

	ɑ	a	æ	i	ɪ	e	ɛ
pharyngeal	+	+	+	-	-	-	-
palatal	-	-	+	+	+	+	+
"tense"	+	-	(-)	+	-	+	-
open	+	+	+	-	-	+	+

Part of the foundation for this approach has already been described elsewhere in this paper. The complete scheme, with definitions and phonetic evidence, will be described in a forthcoming thesis[3] where it will be applied to the solution of a number of phonological problems.

14. "The phonological component accepts as input a structurally analysed string. As output it provides the 'phonetic representation' of this string. The phonetic representation consists of a sequence of 'phonetic segments' each of which is nothing more than a set of 'phonetic feature specifications'..." (p. 164).

BIBLIOGRAPHICAL REFERENCES

Atkinson H.W. 1898. Methods of mouth-mapping. Die Neueren Sprachen 6:494–503

Bell A.M. 1867. Visible speech: universal alphabetics or self-interpreting physiological letters for the writing of all languages in one alphabet. London

Bravmann M. 1934. Materialen und Untersuchungen zu den Phonetischen Lehren der Araber, Göttingen. (Inaugural dissertation). With a German translation of Ibn Sīnā's treatise

Brücke E. 1856. Grundzüger der Physiologie und Systematik der Sprachlaute für Linguisten und Taubstummenlehrer. Vienna

Carmody F.J. 1936. Radiographs of 13 German vowels. Archives Néerlandaises de Phonétique Expérimentale 12:27–33

Carmody F.J. 1937. X-ray studies of speech articulations. Notes and X-ray films of the late Richard T. Holbrook. University of California Publications in Modern Philology, vol. 20, no. 4

Carmody F.J. 1941. An X-ray study of pharyngeal articulation. University of California Publications in Modern Philology, vol. 21, no. 5

Chiba T. and Kajiyama M. 1941. The vowel, its nature and structure. Tokyo

Chlumsky J. 1913. Méthodes pour obtenir le profil de la langue pendant l'articulation. Revue de Phonétique 3:167–173

Chlumsky J. 1914. A review of E. Meyer's article: Das Problem der Vokalspannung. Revue de Phonétique 4:90–95

Chlumsky J., Pauphilet A. and Polland B. 1938. Radiografie francouzských samohlásek a polosamohlásek. Rozpravy České Akademie Věd a Umění, Trida 3, Cislo 75. Prague

Chomsky N. and Halle M. 1968. The sound pattern of English. Englewood Cliffs, NJ

Darembourg C. 1854. Oeuvres anatomiques, physiologiques et médicales de Galien. Paris, 2 vols

Delattre P. 1951. The physiological interpretation of sound spectrograms. Publications of the Modern Languages Association of America 66:864. Reprinted in Studies in French and comparative phonetics, the Hague, 1966

Delattre P. 1971. Pharyngeal features in the consonants of Arabic, German, Spanish, French and American English. Phonetica 23: 129-155

Elert C.-C. 1964. Phonologic studies of quantity in Swedish based on material from Stockholm speakers. Uppsala. Monografier utgivna av Stockholms kommunalförvaltning, no. 27

Fant C.G.M. 1958. Modern instruments and methods for acoustic studies of speech. Acta Polytechnica Scandinavica. Also in Proceedings of the 8th international congress of linguists, Oslo, pp. 282-362

Fant C.G.M. 1960. The acoustic theory of speech production. The Hague

Fant C.G.M. 1964. Formants and cavities. Proceedings of the 5th international congress of phonetic sciences, Münster, pp. 120-141

Fant C.G.M. 1969. Distinctive features and phonetic dimensions. STL-QPSR 2-3/1969: 1-18, Speech Transmission Laboratory, Royal Institute of Technology, Stockholm

Fromkin V. 1970. A reply to P. Ladefoged's "The phonetic framework of generative phonology". UCLA Working Papers in Phonetics no. 14: 34-39

Galen. On the uses of the parts of the human body. French translation by Darembourg (1854).

Grandgent C.H. 1890. Vowel measurements. Publications of the Modern Languages Association of America 5: 148-174

Gunnilstam O. 1974. The theory of local linearity. Journal of Phonetics 2:91–108

Gutzmann H. 1909. Physiologie der Stimme und Sprache. Braunschweig

Gutzmann H. 1930. Röntgenaufnahmen von Zunge und Gaumensegel bei Vokalen und Dauerkonsonanten. Fortschritte auf dem Gebiete der Röntgenstrahlen 41:392–404

Hadding-Koch K. and Abrahamson A.S. 1966. Duration versus spectrum in Swedish vowels: some perceptual experiments. Studia Linguistica 18:94–107

Hála B. 1959. English vowels in phonetic pictures. Rozpravy Československé Akademie Věd, Sešit 5, Ročnik 69

Halle M. 1959. The sound pattern of Russian. The Hague

Halle M. 1964. On the bases of phonology. In Fodor and Katz (eds), The structure of language, Englewood Cliffs, NJ, pp. 324–333

Halle M. and Stevens K.N. 1969. On the feature Advanced Tongue Root. QPR 94:209–215. MIT Research Laboratory of Electronics

Harris K. 1971. Action of the extrinsic tongue musculature in the control of tongue position. Preliminary report. SR 25/26, pp. 87–96, Haskins Laboratory

Hellwag C.F. 1781. Dissertatio inauguralis physiologico-medica de formatione loquelae. Tübingen. Reprinted by Vietor, 1886, Heilbronn

Helmholtz H. von. 1863. Die Lehre von den Tonempfindungen. Braunschweig

Ibn Sīnā. Ca 1000. Risalah fi asbāb ḥuduth al-ḥurūf (a treatise on the points of articulation of the speech sounds). See Bravmann (1934) and Semaan (1963) for translations.

Jakobson R., Fant C.G.M. and Halle M. 1952. Preliminaries to speech analysis. Cambridge, Mass.

Jakobson R. and Halle M. 1964. Tenseness and laxness. In Abercrombie et al. (eds), In honour of Daniel Jones, London. Also in reprints of Jakobson et al. (1952)

Jakobson R. and Halle M. 1968. Phonology in relation to phonetics. In Malmberg (ed), Manual of phonetics, the Hague. Chapt. 13

Jones D. 1967. An outline of English phonetics. 9th edn. Cambridge. First published, 1918

Jones S. 1929. Radiography and pronunciation. The British Journal of Radiography 2: 149-150

Joos M. 1948. Acoustic phonetics. Language Monograph no. 23. Supplement to Language, vol. 24

Kaneko N. 1957. Specific X-ray observations on the movement of the lower jaw, lips and tongue in pronunciation. The Study of Sounds 8: 1-18 and 450-451. Tokyo

Keil F. 1855-1880. Grammatici latini. 7 vols. Leipzig

Kent R.D. 1972. Some considerations in the fluorographic analysis of tongue movements during speech. Phonetica 26: 16-32

Koneczna H. and Zawadowski W. 1956. Obrazy rentgenografizne glosek rosijskich. Warsaw

Korlén G. and Malmberg B. 1959. Tysk ljudlära. Lund

Kruisinga E. 1925. A handbook of presentday English. Part I: English sounds. Utrecht

Ladefoged P. 1964. Some possibilities in speech synthesis. Language and speech 7:205-214

Ladefoged P. 1967. Three areas of experimental phonetics. Oxford. Chapt. 2

Ladefoged P. 1970. The phonetic framework of generative phonology. UCLA Working Papers in Phonetics no. 14:25-32

Ladefoged P. 1971. Preliminaries to linguistic phonetics. Chicago

Ladefoged P., Anthony J.F.K. and Riley C. 1971. Direct measurement of the vocal tract. UCLA Working Papers in Phonetics 19:4-13

Ladefoged P., DeClerk J.L. and Harshman R. 1972. Control of the tongue in vowels. Proceedings of the 7th international congress of phonetic sciences, the Hague, pp. 349-354

Ladefoged P., DeClerk J.L., Lindau M. and Papçun G. 1972. An auditory-motor theory of speech production. UCLA Working Papers in Phonetics 22:48-75

Leky M. 1917. Grundlagen einer allgemeinen Phonetik als Vorstufe zur Sprachwissenschaft. Cologne

Lieberman P. 1972. The speech of primates. The Hague

Lieberman P. and Crelin E.S. 1971. On the speech of Neanderthal man. Linguistic Inquiry 2:203-222. Also reprinted in Lieberman 1972.

Liljencrants J. and Lindblom B. 1972. Numerical simulation of vowel quality systems. The role of perceptual contrast. Language 48: 839-862

Lindau M., Jacobson L. and Ladefoged P. 1972. The feature advanced tongue root. UCLA Working Papers in Phonetics 22:76-94

Lindblom B. 1963. Spectrographic study of vowel reduction. Journal of the Acoustical Society of America 35:1773-1781

Lindblom B. 1972. Phonetics and the description of language. Proceedings of the 7th international congress of phonetic sciences, the Hague, pp. 63-97

Lindblom B. and Sundberg J. 1969a. A quantitative model of vowel production and the distinctive features of Swedish vowels. STL-QPSR 1/1969, pp. 14-32. Speech Transmission Laboratory, Royal Institute of Technology, Stockholm

Lindblom B. and Sundberg J. 1969b. A quantitative theory of cardinal vowels and the teaching of pronunciation. STL-QPSR 2-3/1969, pp. 19-25. Speech Transmission Laboratory, Royal Institute of Technology, Stockholm

Lindblom B. and Sundberg J. 1971. Acoustical consequences of lip, tongue, jaw and larynx movements. Journal of the Acoustical Society of America 50:1166-1179

Lindqvist J. and Sundberg J. 1971. Pharyngeal constrictions. STL-QPSR 4/1971, pp. 26-31. Speech Transmission Laboratory, Royal Institute of Technology, Stockholm

Lloyd R.J. 1890-1892. Speech sounds, their nature and causation. Phonetische Studien, vols 3, 4 and 5

McCawley J.D. 1967. Le rôle d'un système de traits phonologiques dans une théorie du langage. Langages, no. 8, pp. 112-123

MacMillan A.S. and Keleman G. 1952. Radiography of the supraglottic speech organs. Archives of Otolaryngology 55:671-688

MacNeilage P. and Sholes G.N. 1964. An electromyographic study of the tongue during vowel production. Journal of Speech and Hearing Research 17:211-232

Malmberg B. 1952. Le problème du classement des sons du langage et quelques questions connexes. Studia Linguistica 6:1-56

Malmberg B. 1953. Ernst A. Meyer. Studia Linguistica 7:119-122

Malmberg B. 1966. Spansk fonetik

Mazlovă V. 1949. Výslovnost na Zábřežsku, fonetická studie z moravské dialektologie. Prague

Mettas O., Fant C.G.M. and Stålhammar U. 1971. The A-vowels of Parisian French. STL-QPSR 4/1971, pp. 1-8. Speech Transmission Laboratory, Royal Institute of Technology, Stockholm

Meyer E. 1907. Röntgenographische Lautbilder. Medizinisch-Pädagogische Monatschrift für die gesamte Sprachheilkunde. Vol 17

Meyer E. 1910. Untersuchungen über Lautbildung. Festschrift Wilhelm Vietor, pp. 166-248. (Special number of Die Neueren Sprachen)

Meyer E. 1913. Das Problem der Vokalspannung. Die Neueren Sprachen 21:65-86 and 146-171

Minifie F.D., Hixon T.J., Kelsey C.A. and Woodhouse R.J. 1970. Lateral pharyngeal wall movement during speech production. Journal of Speech and Hearing Research 13:584-594

Moll K.L. 1960. Cinefluorographic techniques in speech research. Journal of Speech and Hearing Research 3:227-241

Ohnesorg K. and Švarny O. 1955. Etudes expérimentales des articulations chinoises. Rospravý Československé Akademie Věd, Ročník 65, Sešit 5

Permenter C.E. and Treviño S.N. 1932. An X-ray study of Spanish vowels. Hispania, 15:483-496. Stanford University

Perkell J.S. 1969. Physiology of speech production: results and implications of a quantitative cineradiographic study. Cambridge, Mass.

Perkell J.S. 1971. Physiology of speech production: a preliminary study of two suggested revisions of the features specifying vowels. QPR 102: 123–139. MIT Research Laboratory of Electronics

Peterson G. and Barney H. 1952. Control methods used in a study of the vowels. Journal of the Acoustical Society of America 24: 175–184

Pétursson M. 1974a. Peut-on interpréter les données de la radiocinématographie en fonction du tube acoustique à section uniforme? Phonetica 29:22–79

Pétursson M. 1974b. Les articulations de l'islandais à la lumière de! la radiocinématographie. Société de Linguistique de Paris, collection linguistique no. 68

Polland B. and Hála B. 1926. Artikulace Českych zvuků v roentgenových obrazech. Ná kladem České Akademie Věd a Umění. Prague

Potter R.K., Kopp A.G. and Green H.C. 1947. Visible speech. New York

Potter R.K. and Steinberg J.C. 1950. Toward the specification of speech. Journal of the Acoustical Society of America 22:807–820

Raphael L.J. 1971a. An electromyographic investigation of the tense-lax feature in some English vowels. SR 25/26, pp. 131–140, Haskins Laboratories

Raphael L.J. 1971b. An electromyographic investigation of the feature of tension in some American English vowels. SR 28, pp. 179–191, Haskins Laboratories

Russel O. 1928. The vowel. Columbus, Ohio

Russel O. 1935. Synchronised X-ray, oscillograph, sound and movie experiments, showing the fallacy of vowel triangle and open-close theories. Proceedings of the second international congress of phonetic sciences, London, pp. 198–205

Scheier M. 1909. Die Bedeutung des Röntgenverfahrens für die Physiologie der Sprache und Stimme. Archiv für Laryngologie und Rhinologie, 22: 175–208

Semaan K.I. 1963. Arabic phonetics. Ibn Sīnā's Risālah on the points of articulation of the speech sounds, translated from the mediaevel Arabic. Arthur Jeffery Memorial Monographs no. 2, Lahore

Simon P. 1961. Films radiologiques des articulations et les aspects génétiques des sons du langage. Orbis 10:47-68

Singer C. 1957. A short history of anatomy and physiology from the Greeks to Harvey. New York

Skaličková A. 1955. The Korean vowels. Archiv Orientální 23:29-51

Smith T. 1971. A phonetic study of the phonetic function of the extrinsic tongue muscles. UCLA Working Papers in Phonetics, no 18

Sovijärvi A. 1938. Die gehalteten, geflüsterten und gesungenen Vokale der Finnischen Sprache. Helsinki

Stevens K.N. 1972. The quantal nature of speech, evidence from articulatory-acoustic data. In David E.E. and Denes P.B. (eds.): Human communication, a unified view, pp. 51-56

Stevens K.N. and House A.S. 1955. Development of a quantitative description of vowel articulation. Journal of the Acoustical Society of America 27:484-495

Stevens K.N. and House A.S. 1961. An acoustical theory of vowel production and some of its implications. Journal of Speech and Hearing Research 4:303-320

Stevens K.N. and House A.S. 1963. Perturbation of vowel articulations by consonantal context. Journal of Speech and Hearing Research 6:111-128

Stewart J.M. 1967. Tongue root position in Akan vowel harmony. Phonetica 16:185-204

Strenger F. 1968. Radiographic, palatographic and labiographic methods in phonetics. In Malmberg B. (ed.): Manual of phonetics, Amsterdam, pp. 334-364

Subtelny J.D., Pruzansky S. and Subtelny J. 1957. The application of Roentgenography in the study of speech. In Kaiser L. (ed.): Manual of phonetics, Amsterdam, pp. 166-179

Sundberg J. 1969. Articulatory differences between spoken and sung vowels in singers. STL-QPSR 1/1969:33-45, Speech Transmission Laboratory, Royal Institute of Technology, Stockholm

Tiffany W.R. 1959. Non-random sources of variation in vowel quality. Journal of Speech and Hearing Research 2:305-317

Vennemann T. and Ladefoged P. 1971. Phonetic features and phonological features. UCLA Working Papers in Phonetics 21:13:24

Vietor W. 1914. Zur Systematik der Vokalartikulation. Miscellanea Phonetica 1:1-5

Wang W.S.-Y. 1968. Vowel Features, paired variables and the English vowel shift. Language 44:695-708

Wängler H.H. 1961. Atlas deutscher Sprachlaute. Berlin

Whitney W.D. 1962. The Atharva-Veda Prātiçākhya, or Çaunakīyā Çaturādhyāyikā: text, translation and notes. Journal of the American Oriental Society 7:333-615

Wood S. 1971. A spectrographic study of allophonic variation and vowel reduction in West Greenlandic Eskimo. Working Papers no. 4, pp. 58-94, Phonetics Laboratory, Department of General Linguistics, Lund University. See note 3

Zemlin W.R. 1968. Speech and hearing science - anatomy and physiology. Englewood Cliffs, N.J.