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THE PHONETIC VALUE OF VOWELS

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[The aural evaluation of vowel sounds is a basic problem in both experimental and applied phonetics. This paper deals with the judgment of phonetic equivalence in the elementary case of sustained vowels. The definition of the phonetic value of vowels in terms of physiological and acoustical dimensions is considered, and the conventional vowel diagram is discussed as a means of representing vowel sounds in a multidimensional phonetic space.]

1. PHONETIC VALUE

1.1. SPEECH PATTERNS. The sound waves generated in the production of speech are complex in frequency composition and vary markedly with time. The patterns of 'visible speech'¹ show that there is an almost continuous change in the frequency composition of speech as a function of time. The distribution of energy as a function of frequency, and the changes in this energy-frequency distribution as a function of time are both basic factors in speech.

We may regard the former, i.e. the distribution of energy as a function of frequency, as the **FORM** in acoustical speech patterns. The changes in this form as a function of time make the gesture-like character of the acoustical patterns of speech.² These two aspects of speech patterns are shown in the spectrograms³ of Fig. 1. The upper broad-band pattern shows the time variations of the distribution of energy in frequency; these patterns reflect the movements in speech. The lower portion shows four amplitude sections⁴ or spectra of the speech waves at four selected points in the continuum; these sections illustrate the basic form from which the gestures of speech are constructed.

1.2. SUSTAINED VOWELS. To students of speech, it is common knowledge that representative spectral forms may be isolated from speech and produced in a relatively sustained manner. Such isolation is readily achieved in the case of the vowels and of most consonants, such as fricatives and nasals.

The production and aural identification of sustained vowels and consonants is somewhat different from an individual's normal language experience involving

¹ See R. K. Potter, G. A. Kopp, and H. Green, *Visible speech* 65-269 (New York, 1947); R. K. Potter and G. E. Peterson, *The representation of vowels and their movements*, *Journal of the Acoustical Society of America* 20.528-35 (1948).

² Cf. Potter and Peterson, *op.cit.* (fn. 1).

³ See W. Koenig, H. K. Dunn, and L. Y. Lacy, *The sound spectrograph*, *Jour. Ac. Soc. Am.* 17.19-49 (1946); M. Joos, *Acoustic phonetics*, Index s.v. *spectrogram* (Lang. Monogr. No. 23; 1948).

⁴ See L. G. Kerste, *Amplitude cross-section representation with the sound spectrograph*, *Jour. Ac. Soc. Am.* 20.796-801 (1948).

The amplitude sections shown in Fig. 1 were made with a 45-cycle analyzing filter. Zero frequency is shown by the long line at the top of each of the four sections, and the frequency and amplitude scales are placed along the sides. The first section is taken from the beginning of the [r] and shows the evenly spaced harmonics of the voiced sound. The second section is taken from the [s] and shows the irregular spectrum of the fricative sound. The third section is taken from the explosion of the [t], the fourth from the [r].

continuous speech. The layman often finds it rather difficult to form sustained vowels and to discriminate among them. However, the fact that these sustained forms are fundamental in speech is well illustrated by the experience of speech pathologists. In the correction of articulatory disorders, for example, it is generally recognized that a sound must be taught in isolation before it is taught in context, if the teaching is to be effective.⁵

It should be noted that there is a physiological limit to the degree to which steady tones can be produced by the human vocal mechanism. The variations which appear in sustained vowels often differ in character with different speakers. This fact suggests that such variations are of secondary importance in defining the vowel. Nevertheless, they doubtless contribute considerably to the naturalness of the vowel; that is, they help to identify the production of the vowel with a human vocal mechanism.

1.3. VOWEL QUALITIES. The sustained vowel affords a simple and basic element for study, since it is essentially of constant form; that is, it provides a means of studying the spectral form from which the acoustical gestures of continuous speech are made.

There are four aspects of a sustained vowel which normally can be recognized: fundamental pitch, loudness, voice quality, and phonetic quality. The definitions of these several aspects (or qualities, as Bloch has called them⁶) in acoustical or auditory terms is one of the major projects of present-day phonetic research. The general relationship of these subjective qualities to the operation of the vocal mechanism, it is true, has been reasonably well understood for some time.⁷

The fundamental pitch⁸ of the vowel depends chiefly on the frequency of the opening and closing of the vocal cords. The loudness, under fixed conditions of listening, depends on neuro-muscular adjustments of the vocal cords and the breath force employed in producing the vowel. Voice quality (such as 'rasping', 'harsh', 'hoarse', 'breathy') depends primarily on the physiological structure of the vocal cords and the manner in which they are used. The phonetic quality, or phonetic value, of a vowel depends mainly on the cavity shapes and relationships within the mouth, the nose, and the pharynxes. (Nasality, in its various forms and degrees, is here associated with phonetic value.)

It is recognized that both organically and acoustically there is coupling among certain elements of the vocal mechanism, so that these qualities are not entirely independent of each other. Thus, high pitch and nasality very frequently occur together; a breathy voice is often a weak voice.

1.4. PHONEMIC VALUE. The four aspects of vowels named above are employed in various ways in the word signs⁹ of all languages. Phonetic value, as here defined, is only one of the aspects of vowels which may be employed in the trans-

⁵ Cf. C. Van Riper, *Speech correction: Principles and methods* (New York, 1939).

⁶ B. Bloch, *Studies in colloquial Japanese IV: Phonemics*, Lg. 26.88-97 (1950).

⁷ See R. West, L. Kennedy, and A. Carr, *The rehabilitation of speech* (New York, 1937).

⁸ On the terms 'fundamental pitch' and 'loudness' see Proposed American standard acoustical terminology 21, 22 (published by the American Standards Association, New York, 1949).

⁹ C. W. Morris, *Foundations of the theory of signs* (International encyclopedia of unified science, Vol. 1, No. 2; Chicago, 1938).

mission of meaning. It is a fundamental vowel quality in the sense that the acoustical factors basic to phonetic value are common to different languages.

In contrast, phonemic value often involves more than one of the four characteristics of vowels; the characteristics essential to the transmission of meaning vary

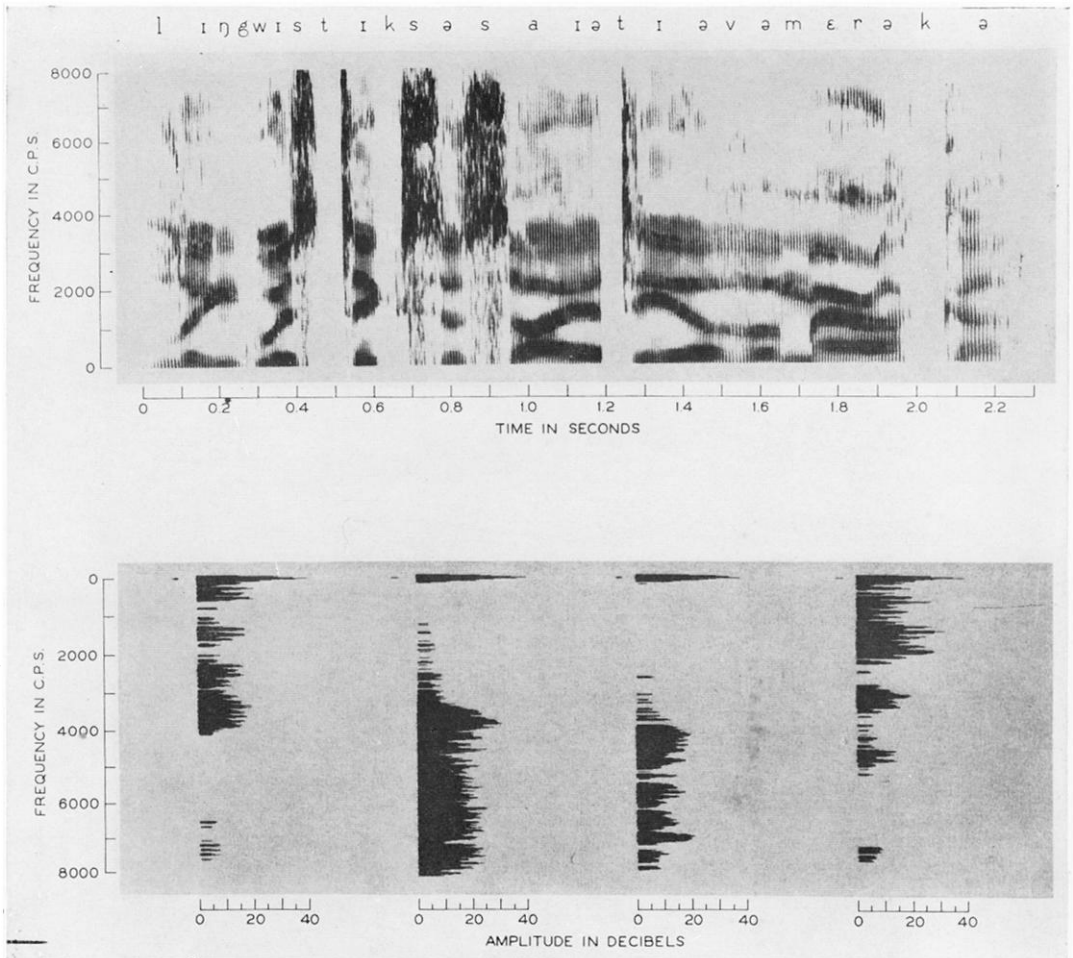


FIG. 1. Broad-band acoustical spectrogram of the phrase *Linguistic Society of America*, with amplitude sections taken at the time positions which align with the bases of the sections.

from language to language. The phonemic value to be assigned to a specific vowel sound will therefore depend on the particular language in which the sound is to be evaluated.

Two basic problems are the relation of sustained vowels to the vowels of continuous speech,¹⁰ and the relation of the vowels of continuous speech to the trans-

¹⁰ The term 'speech' is employed here as defined by B. Bloch, A set of postulates for phonemic analysis, Lg. 24.7 (1948).

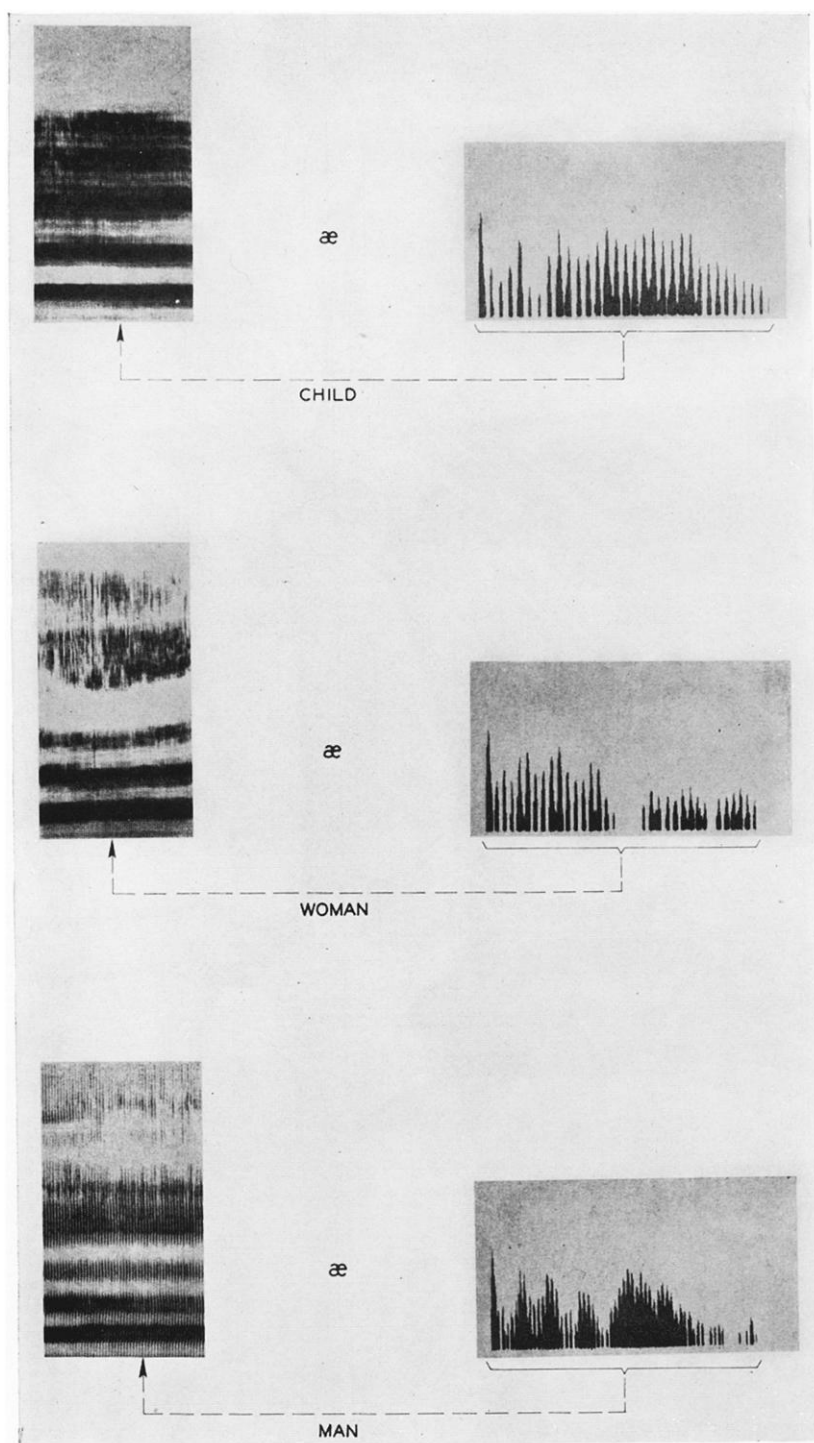


FIG. 2. Broad-band acoustic spectrograms and amplitude sections of the vowel [æ] pronounced by a child, a woman, and a man.

mission of meaning, i.e. to semiosis. The first of these problems, which is essentially a problem in experimental phonetics and audition, has been discussed by Joos;¹¹ the second, a problem of phonemics, has been discussed by Bloch and Pike,¹² among others.

1.5. VOWEL CLASSIFICATION. The various aspects or qualities of vowels are probably best defined in operational terms.¹³ A group of sustained vowel sounds may be classified according to any of their four qualities: the magnitude of the fundamental pitch, the loudness, the voice quality, or the phonetic value. The validity of classification by these various subjective qualities is probably best demonstrated by the fact that a group of phoneticians or linguists, arranging a large sample of sounds in different classes according to these criteria, would on the whole agree with each other in their classification.

A study of the acoustical characteristics of any one of the four aspects of sustained vowels is complicated by the presence of the other three. These characteristics can be understood, however, by relating subjective evaluations of the qualities to physical measurements of the vowels. Several attacks on the problem are possible. Thus, one approach to the study of phonetic value would be to select a group of vowels which had been judged to have essentially the same phonetic value but which differed in the other three aspects: those physical factors or relationships which were found to be common to such a set of samples would then define their phonetic value.

2. PHONETIC EQUIVALENCE

2.1. EQUIVALENCE IN SPEECH. It is a common experience that the speech of a child may carry much the same information as that of an adult. The fact that a certain equivalence or sameness may be observed in the vowels and consonants of different speakers is fundamental to most of the work done in the area of experimental phonetics and to the practical applications of phonetics in teaching.

The concept of equivalence is particularly important here. Observations of equivalence are basic in all measurements, and the judgment of equivalence is the most fundamental step in the construction of psycho-physical scales.¹⁴

Familiarity with the relationships which afford phonetic equivalence undoubtedly results from a speaker's experience with his native language. In speaking his language, he probably acquires certain sound patterns as references, to which he then refers the speech sounds which he hears. But when, through his language experience, he has acquired familiarity with the basic subjective relationships which afford phonetic equivalence, he need no longer be bound to any particular language. By listening to speech sounds objectively, he can usually learn to recognize the presence or absence of phonetic equivalence between sounds formed in almost any manner by the human vocal mechanisms; the ability to learn a foreign language illustrates this fact. It is even possible for one speaker to teach

¹¹ M. Joos, *Acoustic phonetics* (Lang. Monogr. No. 23; 1948).

¹² Bloch, *op.cit.* (fn. 6 and 10); K. L. Pike, *Tone languages* (Ann Arbor, Mich., 1948).

¹³ P. W. Bridgman, *The nature of physical theory* 5-15 (Princeton, 1936).

¹⁴ See S. S. Stevens, *On the theory of scales of measurement*, *Science* 103.677-80 (1946); J. M. Cowan and B. Bloch, *An experimental study of pause in English grammar*, *American Speech* 23.89-99 (1948).

another the sustained vowels of a foreign language without using any words of the language whatever.

While a speaker's first experiences with phonetically equivalent sounds normally come about through his native language, the same principles are probably fundamental to all languages. The conclusion is that the subjective relationships which afford phonetic equivalence are common to different languages.

An analogy is the individual's learning of polygonal forms. He must have visual experience with such forms before he can discriminate among them. By this experience he learns certain fundamental principles for comparing forms, such as observing the number and type of angles or the relative length of the sides. Once he has learned these principles, he can recognize similarities and differences among polygons with which he has had no previous experience. The process is simply one of generalization.

The identification of equivalent vowel forms, even when portions of the vowel are eliminated by filters, has been discussed by Chiba and Kajiyama.¹⁵ Pitts and McCulloch have presented a mathematical treatment of the neuro-physiological aspects of the identification of forms in both audition and vision.¹⁶

2.2. JUDGING PHONETIC EQUIVALENCE. It is not unlikely that one's judgment that two vowel sounds are or are not phonetically equivalent is affected by the specific listening conditions, including preceding acoustical stimuli. Some systematic procedure is therefore necessary to insure consistent evaluations.

There are various ways of selecting a group of phonetically equivalent vowels for experimental study. Recording is essential. In order to obtain well sustained vowels it is necessary to choose speakers with previous training, or to instruct the subjects during the recording. A carefully spoken recorded vowel which can be repeated several times for the subject as a point of reference is valuable, and makes it possible to study vowels outside the speaker's previous language experience.

To obtain aural evaluations of such a set of vowels it is desirable to have a group of observers who are experienced in working with sustained vowels. One possible approach to the selection of equivalent vowels is to use again the recorded vowel chosen previously as a reference point for the speakers, this time as a reference point for the observers.

Since of course no two vowels are precisely alike, the results will represent some type of distribution. Repeated tests with each listener and evaluations by several listeners are required to obtain the most dependable selection of vowels.

2.3. VOWEL FORM. Present indications are that phonetic equivalence is primarily based upon certain aspects of the form of the vowel spectrum. When one speaker is asked to reproduce a sound that another speaker has pronounced, it is found that absolute values of energy, frequency, and time are not preserved. This becomes evident in graphic analysis, of the kind shown in the spectrogram of Fig. 1. In particular, the major regions of energy concentration (the vowel

¹⁵ T. Chiba and M. Kajiyama, *The vowel: Its nature and structure* 174-226 (Tokyo, 1941).

¹⁶ W. Pitts and W. S. McCulloch, *How we know universals: The perception of auditory and visual forms*, *Bulletin of mathematical biophysics* 9.127-47 (1947).

formants) for women are generally higher in frequency than those for men; and the regions for children lie higher still. This fact is illustrated in the three spectrograms of the vowel [æ] shown in Fig. 2.

It is possible for a child to learn to speak by hearing only the speech of adults—i.e. without learning any speech patterns from other children. (This type of speech development probably predominates for the first child in the family, who normally learns his first speech sounds from his parents.) Since the child's regions of energy concentration (formants) will not fall in the adult positions, it follows that there are certain aspects of the form of the spectrum to which the child learns to attend.

In voices of high fundamental pitch, the harmonics are fewer and more widely spaced. It is not unreasonable to assume that in many cases the major regions of energy concentration for a child's voice may be less clearly defined, or less sharply differentiated from each other, than those for a voice of low fundamental pitch. A child with extremely high fundamental pitch may have only two or three harmonics available to define the first two important formants of a vowel; in such a case the phonetic values which the child can achieve will depend upon the location of the harmonics, and he may be unable to produce certain values at all. (The same problems can be observed in singing high notes, and in the production of vowels in falsetto by a man.) As the fundamental pitch decreases, there is doubtless a relatively continuous transition from the difficulties of high pitch to the well defined phonetic values of low pitch. It follows that an observer will occasionally be uncertain about the phonetic value of a vowel produced by a child, particularly when the fundamental pitch is unusually high.

These conclusions, it is believed, correlate rather well with the experience of those who have worked with children's speech. On the other hand, language and speech teachers have found that at a moderate fundamental pitch a child usually can be taught to produce sustained vowels which are very similar in phonetic value to those of an adult (cf. fn. 5).

We have observed above that sustained vowels produced by different speakers are sometimes judged to be phonetically equivalent. Similar equivalence could obviously be found when such sounds are accurately recorded and reproduced, or when they are precisely synthesized. This suggests that the same sort of equivalence may be recognized among certain types of complex tones generated by other means than the human vocal mechanism; instrumental tones in music are an example.

3. THE VOWEL DIAGRAM AND PHONETIC VALUE

3.1. VOWEL FORMATION. It has long been recognized that a consistent method of designating the values of vowel sounds is basic to both experimental and applied phonetics. A fundamental question in experimental phonetics is whether sustained vowel sounds which are judged aurally to be phonetically equivalent have similar organic formations (and thus similar acoustical patterns), or whether they have similar sensory patterns after the signals have passed the non-linearities and the transformations of the auditory apparatus.¹⁷

¹⁷ The non-linearity of the ear is illustrated by the fact that equal increments in the

The extensive use of the well-known vowel diagram strongly suggests that, when nasality and lip rounding are held constant, vowels can be successfully ordered in two dimensions. The horizontal and vertical dimensions of the vowel quadrilateral are related in some manner to positions in the vocal cavities. X-ray pictures which have been made, however, indicate that there is some question as to the precise aspects of the vocal-cavity positions which these dimensions represent.¹⁸

To describe completely the cavity formation of a sustained vowel, a very large number of physiological measurements would be required. If it is enough to describe the position of each organ approximately, then the specification of only six or seven physiological variables will be adequate: (1) the position of the hump of the tongue along the vocal tract; (2) the degree of constriction between the tongue hump and the palate or pharyngeal wall; (3) the length of the tongue constriction; (4) the degree of lip separation; (5) the degree of lip rounding; (6) the degree of jaw separation; (7) the magnitude of the opening between the nasal and oral pharynges, as determined by the velum. Some so-called retroflex or *r*-colored vowels involve an additional tongue-to-palate constriction, and will thus require that two more physiological variables be specified: the position and the degree of the second tongue constriction.

In the various vowel series, several of the variables are closely correlated, so that for practical purposes a two-dimensional representation of the vowels is sometimes usable. Thus, in the rounded front vowels the degree of jaw separation, the magnitude of lip separation, and the degree of lip rounding are all closely correlated with the degree of constriction between tongue and palate. In the rounded back vowels these same three variables appear to be closely associated with the position of the tongue constriction along the vocal tract. This follows from X-ray evidence, which shows that the hump of the tongue moves progressively into the pharynx in the series [u-o-ɔ] (see fn. 18). The same fact has been observed by Dunn in the synthesis of vowels with an electrical analog to the vocal tract.¹⁹

It appears, then, that the coordinates of the vowel quadrilateral are ambiguous when both front and back vowels are shown in the same two-dimensional physiological system. To form a consistent physiological vowel diagram, more than two dimensions would be required.

3.2. AURAL CHARACTERISTICS OF VOWELS. Joos (op.cit. in fn. 11) and Delattre²⁰ have suggested that the conventional vowel quadrilateral is essentially auditory

intensity of a tone do not always correspond to equal increments in its loudness. A transformation in the signal occurs when the wave motion within the cochlea is converted to the form of nerve impulses.

¹⁸ See G. O. Russell, *Speech and voice* (New York, 1931); C. E. Parmenter and S. N. Treviño, Vowel perceptions as shown by X-ray, *Quarterly journal of speech* 18.351-69 (1932); F. J. Carmody, X-ray studies of speech articulation (Univ. Cal. Publ. in Modern Philology, Vol. 20, No. 4; 1937).

¹⁹ H. K. Dunn, The calculation of vowel resonance and an electrical vocal tract, *Jour. Ac. Soc. Am.* 22.740-53 (1950).

²⁰ P. Delattre, Un triangle acoustique des voyelles orales du français, *French Review* 21.477-84 (1948).

rather than articulatory. The type of information which supports this argument is shown in the formant plots of Fig. 3.

A concise definition of a formant is yet to be formulated; but a rough definition in terms of energy concentration has served well enough to show the fundamental importance of such a concept. Further, Dunn (cf. fn. 19) has shown the basic acoustical significance of the formant positions in frequency. Joos, Delattre, and Potter and Peterson (cf. fnn. 11, 20, and 1 respectively) have represented the first two formants by single frequency values; and for a single speaker the basic relationships among the vowels are preserved when the frequency of the first formant is plotted against the frequency of the second formant.

Figs. 3A and 3B chart a number of sustained vowels (each one pronounced twice) spoken by two different phoneticians. The vowels of one speaker are shown in Fig. 3A, those of the other in Fig. 3B. Vowels are plotted as small circles; neighboring circles represent the two repetitions of the same vowel. Circles representing unrounded vowels are connected by a solid-line loop; circles representing rounded vowels are connected by a dashed-line loop.

The spacing of the formant scales shown in these graphs is according to the subjective pitch or mel scale; that is, equal spacings represent equal increments of pitch for pure tones.²¹ The mel spacing is chosen so as to show frequency in accord with its auditory effects. These graphs show that for a single speaker the relationships among the rounded or among the unrounded non-nasal vowels are rather well defined by the first two formants.

The native languages of the two speakers of Fig. 3 are different—English for 3A and French for 3B; yet it can be seen that the general relationships among their vowels are similar. Of importance also is the fact that when vowels are plotted on these scales the increments are roughly equal between most of the adjacent vowels of the front and back series.

The similarity between this type of graph and the familiar vowel diagram of the International Phonetic Association²² is obvious.

3.3. THE DIMENSIONS OF VOWELS. The relation of the acoustical patterns of vowels to their physiological formation has been studied by Dunn (cf. fn. 19). He has shown that no single acoustical parameter, such as a particular formant frequency, is dependent solely upon any single physiological parameter. In general, any element of the acoustical pattern of a sustained vowel is determined by several factors in the vocal-cavity formation of the vowel.

The number of acoustical variables required to differentiate sustained vowel sounds which differ in phonetic value is of considerable interest. To specify the physical nature of a given vowel completely, it is obvious that a large number of dimensions would be necessary; yet linguists and students of experimental pho-

²¹ S. S. Stevens and J. Volkman, The relation of pitch to frequency: A revised scale, *American journal of psychology* 53.329–53 (1940).

A mel is defined as the psycho-physical unit of pitch. A pitch scale may be derived from estimates of the relative height of tones. The unit is arbitrarily chosen such that a frequency of 1000 cps at 40 decibels above normal threshold has a pitch of 1000 mels.

²² For instance as shown in P. Passy and D. Jones, *The principles of the IPA* (Supplement to *Le maître phonétique* for September–October 1912).

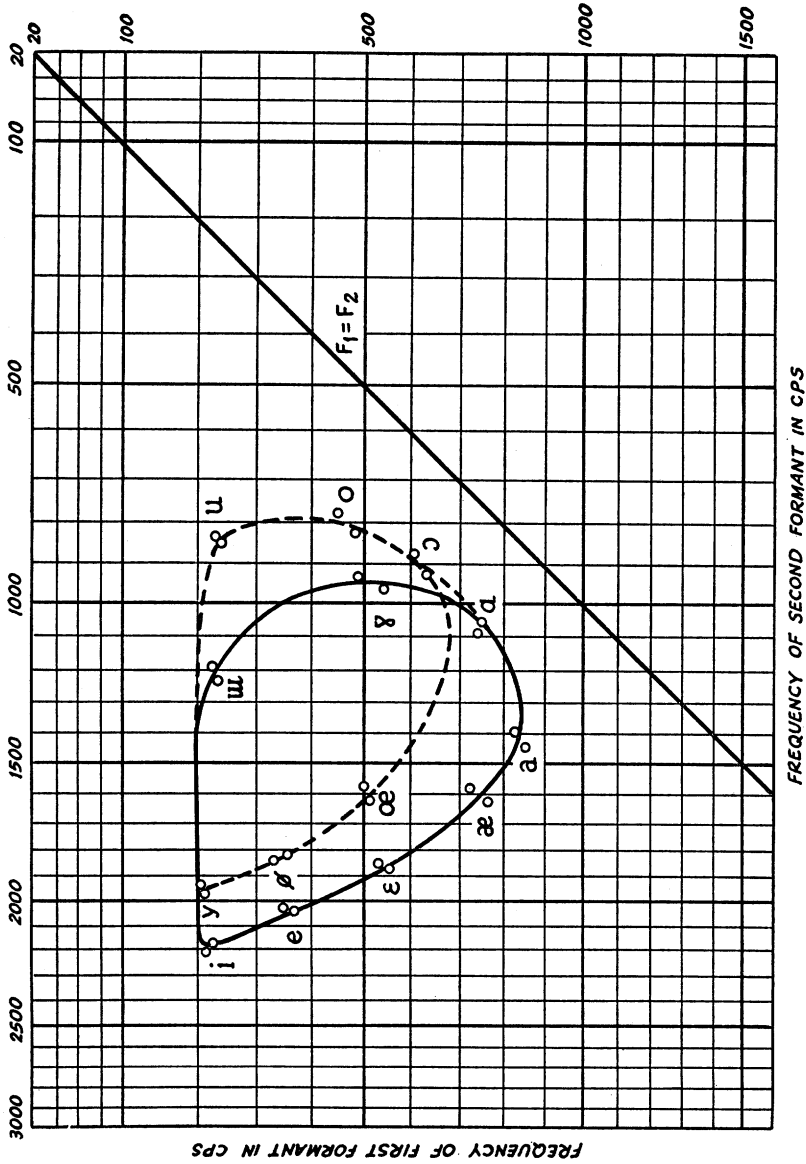


FIG. 3A. A plot of the first formant versus the second formant for sustained vowels pronounced by a native speaker of English. Each vowel was spoken twice. Positions connected by a solid line represent unrounded vowels; positions connected by a dashed line represent rounded vowels.

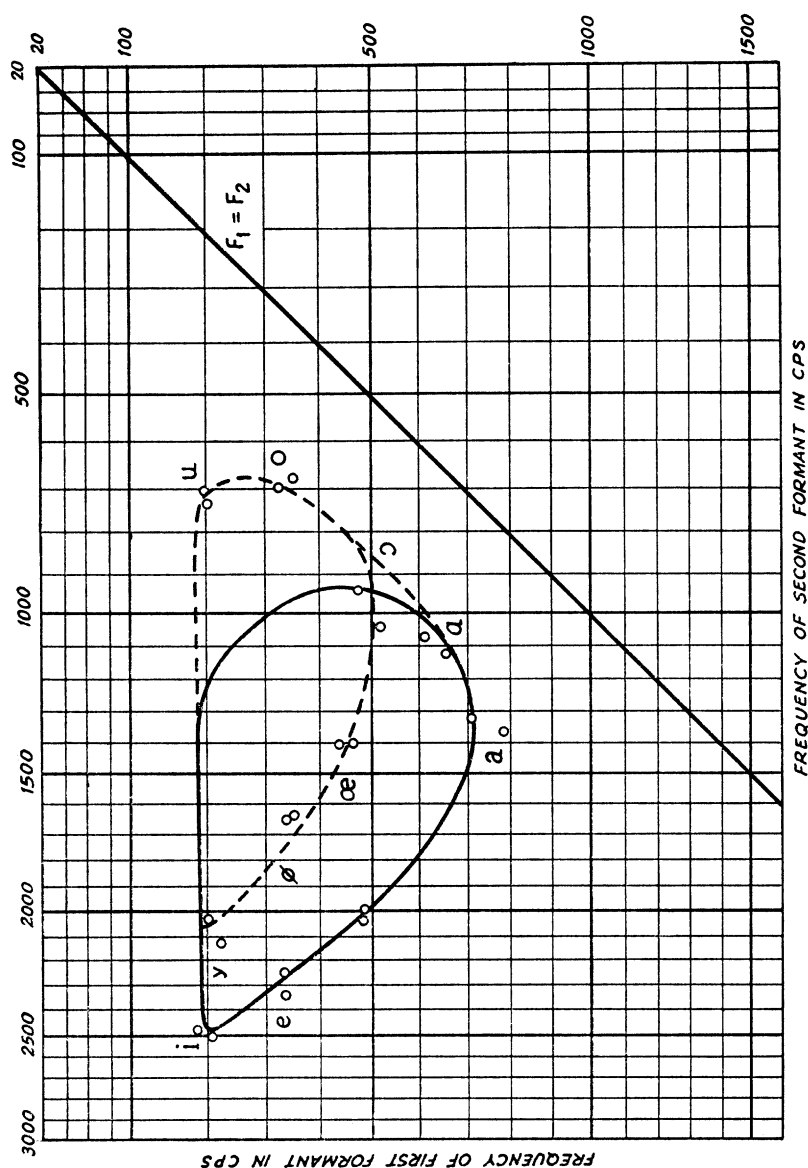


FIG. 3B. A plot of the first formant versus the second formant for sustained vowels pronounced by a native speaker of French. Details as in Fig. 3A.

netics have found that the phonetic value of a vowel can be specified rather well with a fairly limited number of variables. On the other hand, there is evidence that more than the first two formants are required.

The two loops shown in each plot of Fig. 3 have essentially the same cavity formations except for lip rounding. It should be noted that in the rounded (dashed-line) loops of these figures, a different degree of lip rounding is associated with each vowel of the front or back series. Actually, the lips can be pro-

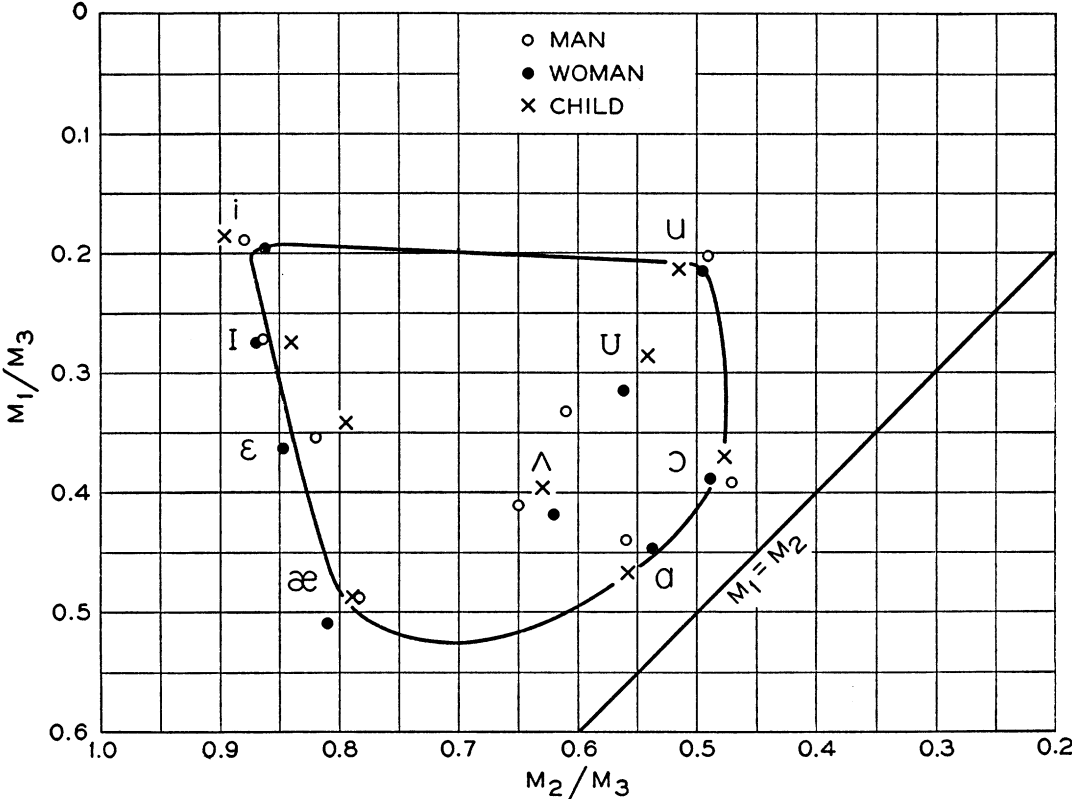


FIG. 4. A plot of the ratios of the first three formants (1/3 and 2/3) for approximately phonetically equivalent sustained vowels pronounced by a man, a woman, and a child.

gressively shaped from unrounded to fully rounded position, so that there is a continuum between the members of such a pair as [e, ø].

In these vowel plots, unrounded vowels can be formed anywhere within the solid-line loop, and rounded vowels can be formed anywhere within the dashed-line loop. Over a considerable portion of these two-dimensional plots, the two loops overlap, so that for a single speaker one or more dimensions in addition to the first two formants would be necessary to differentiate between corresponding rounded and unrounded vowels.

That more than two dimensions are needed to distinguish among vowels is demonstrated also by the aural experience of practical phoneticians. To indicate

gradations intermediate between [i] and [y] or between [e] and [ø], phoneticians do not use modifiers of the same type as those that show positions intermediate between [i] and [e]. It seems clear, therefore, that the relations among three such vowels as [i, y, e] cannot be adequately portrayed with only two variables.

3.4. THE VOWEL DIAGRAM. Since vowel sounds are received by the auditory mechanism, their evaluation must be based upon patterns created in that sensory system. These auditory patterns result from certain functions and transformations of the acoustical signal.

The variables which are significant in determining phonetic value in these auditory patterns may be regarded as the dimensions of a multidimensional phonetic space. To a linguist or a phonetician, the conventional vowel diagram has a broad and abstract language reference, and is relatively independent of any single language. This reference is somewhat vague, but it is very probable that for such a person there are vowel spacings in the diagram which represent equal steps along certain dimensions of the phonetic space.

As suggested previously, when the significant dimensions of this phonetic space have been properly identified, the phonetic value of any vowel can be specified quantitatively in these dimensions. Further, the phonetic value of any vowel can then be predicted from physical measurements of the signal. If the physical factors which define phonetic value can be discovered and presented in their phonetically significant form, then phonetically equivalent sustained vowels should be represented by essentially the same values.

A two-dimensional illustration of this possibility is shown in Fig. 4. The vowels plotted in this figure were recorded by three different speakers: a man, a woman, and a child, with coaching from the author in the formation of those sounds which appeared to deviate from his own vowels. The vowels produced by the three speakers are thus only approximately phonetically equivalent. All the vowels were pronounced without nasality and at a normal loudness level. The speakers were instructed to disregard voice quality and pitch, and to direct all their efforts toward imitating the phonetic value of the vowels presented as models.

The frequency positions of the first three formants were measured for each of the vowels shown, and these frequency values were then converted into mels. By employing mel ratios of the formants, only the general form of the spectral pattern is maintained. Fig. 4 shows that there is no significant displacement among the vowel diagrams of the three different speakers.

This finding would indicate that the phonetic value of a vowel, and hence also the phonetic equivalence of successive vowels, depends not on the absolute frequencies of the vowel formants but rather on the ratios existing among the formants—specifically, the ratios of the first and second to the third.