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REEDS II, James Alexander, 1921-
FRONT VOWEL APERTURE AND DIFFUSENESS IN MIDWESTERN AMERICAN ENGLISH.

The University of Michigan, Ph.D., 1966
Language and Literature, general

University Microfilms, Inc., Ann Arbor, Michigan

FRONT VOWEL APERTURE AND DIFFUSENESS IN MIDWESTERN AMERICAN ENGLISH

by

James Alexander Reeds II

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in the
University of Michigan
1966

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Abstract

FRONT VOWEL APERTURE AND DIFFUSENESS IN MIDWESTERN AMERICAN ENGLISH

By James Alexander Reeds II

The problem is how best to describe acoustic phonetic differencesbetween the front vowels of Midwestern American English so as to account for phonetic data in phonemic analysis.

The dissertation outlines a rationale for the inclusion of experimental phonetics within the natural sciences and for incorporating phonetic data in statements, on a higher level of abstraction, within the science of linguistics. A list of assumptions is provided which might govern the mapping of phonetic data onto phonemic descriptions. An understanding of the meaning of phonetic similarity is crucial.

Following Malmberg (1962), several levels of abstraction in phonological analysis are discussed in an attempt to show how one kind of acoustic phonetic research relates to phonemics.

Phonetic characteristics as described in traditional terms are compared with acoustic phonetic parameters involving the first two formant frequencies. An experiment in the description of Midwestern American English front vowels is outlined. Two new parameters are proposed: <u>diffuseness</u> and <u>aperture</u>.

<u>Diffuseness</u> is defined as the logarithm to the base two of the ratio between the second and the first formants. <u>Aperture</u> is an oblique distance in logarithmic F_2F_1 space between an arbitrary reference point and an experimental point. For a given set of data, measurement is made along an empirically derived standard aperture line of slope m and intercept b, according to the formula

$$a = \frac{-\frac{b}{m} - x - ym}{\sqrt{m^2 + 1}} ,$$

where x is the ratio in octaves between the frequency of the second formant and an arbitrary reference frequency, and y is

the ratio in octaves between the frequency of the first formant and a reference frequency. The standard aperture line for the present corpus of closed monosyllabic words had a slope of ca. -3.

Several hundred samples of a selected list of words were analysed spectrographically, the formants were measured to a high degree of accuracy, and the resultant data were processed by a digital computer to give plots and tables of changes in diffuseness and aperture.

The results showed that the vowels of _meat_, _mate_, _mitt_, and _mat_ increased in aperture and decreased in diffuseness in the stated order. The conclusion is suggested that on a higher, i.e. phonemic, level of abstraction, the vowels of _meat_ and _mitt_ (or _beat_ and _bit_, _peach_ and _pitch_) are not similar.

to Hedy

Acknowledgements

This dissertation was supported in part by a fellowship sponsored by International Business Machines Corporation, by a grant from the Horace H. Rackham School of Graduate Studies, and by a fellowship sponsored by the National Institutes of Health. The author wishes to express his appreciation to the above-mentioned institutions for their subsidies. The experimental work in connection with the dissertation was performed in the Communication Sciences Laboratory of The University of Michigan, Professor Gordon E. Peterson, Director. Without the use of the facilities of that laboratory and of the Computer Center, this dissertation could not have been completed.

The author also wishes to express his gratitude for the encouragement and support offered by the University of Detroit, The Very Reverend Malcolm Caron, S.J., President, and by the English Department, Professor John Mahoney, Chairman. The reduction in teaching load during several semesters was very helpful. The Department of Slavic Languages and Literatures of the University of Michigan, Professor John Mersereau, Chairman, is to be thanked

for the use of office space during the final stages of the writing of the dissertation.

In preliminary studies connected with the dissertation the author received much benefit from the counsel offered by friends and former colleagues in the Communication Sciences Laboratory, in particular Professor William S.-Y. Wang, Professor Ilse Lehiste, and Dr. John Hanne. Several professors not now officially concerned with this dissertation have given the author more advice than he was wise enough to use. In this connection is to be mentioned Professor Ladislav Matejka of the Department of Slavic Languages and Literatures, who has not only lent the author a desk but has given advice and assistance in a number of ways. Professor Clyde Coombs of the Psychology Department has encouraged the author to believe that psychological scaling is an important part of phonetic research.

Very emphatic expressions of gratitude must be offered to Professor Peterson and Professor June Shoup of the Communication Sciences Laboratory for the hours of patient help given over a long period of time. The author acknowledges his debt to Professor J. C. Catford, Director of the English Language Institute, for advice tardily sought. Professor Peter Fodale has also given help on several occasions.

The author's son, James Alexander Reeds III, a student in the College of Literature, Science, and the Arts, is to be thanked for the writing of the computation program, for assistance in keypunching, mathematical expressions, and a wide variety of tasks, large and small.

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Chapter 1. Introduction

Experimental phonetics and linguistics

The present dissertation in linguistics is a laboratory investigation of a certain problem in phonetics. One approach that might be appropriate would be to identify the frame of reference within which a solution to the problem is sought, before the problem is discussed in detail. An attempt is made here to distinguish between two branches of phonology, namely phonetics and phonemics.[1] Phonology is conceived of as a set of patterns of linguistic behavior. In broad terms, the observation and description of linguistic behavior is seen as an empirical science sharing certain features with other empirical sciences of human behavior. Explicit definitions of the terms _phonemics_, _linguistics_, _linguistic behavior_, _human behavior_, and _empirical science_ are not attempted here. The scope of inquiry is delimited instead by a set of _assumptions_ below, some of which are intended to apply to human behavior generally and some to the more restricted area of phonetic behavior.

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[1] The present use of the term _phonology_, although common enough in linguistics, is not the only use of the term.

It should be borne in mind that the dissertation is intended primarily as a contribution to the field of phonetics rather than phonemics. The conclusions are, to be sure, offered in a form that might facilitate application to various models for the phonemic analysis of English, but the details of that application are left to the reader.

It would seem that the role of instrumental experimental phonetics within linguistics does not lie in the mere collection of facts about speech. To the extent that phonetics is a natural science (Trubetzkoy, 1929), its purpose is the formulation of scientific generalization based on objective observation and, where appropriate, measurement (Campbell, 1919). Further constraints apply to the science of linguistics generally and to its various branches. In particular, there is one constraint under which linguists, if not other scientists, must operate: that differences in form must be related to differences in function, and the strategy of observation, if not the statement of description, must proceed in that order, form before function. Pursuing the view expressed above, it is held in this dissertation that the task of the phonetician is three-fold: 1. to accumulate, by whatever means available, whatever facts are needed to demonstrate what systematic differences in speech form are associated with distinctions in language function; 2. to discover and identify those distinctions in language function, i.e. oppositions between phonemes or contrasts within (short) strings of phonemes; and 3. to state those differences in form and distinctions in function in an economical way that does not violate the evidence at hand. The means available to the phonetician are introspection and subjective observation if necessary, but verifiable experiment with instrumental measurement if possible.

The existence of differences in speech implies opposition with similarity (Bloomfield, 1926). The phonemes of a language are a small set, called a <u>paradigm</u>, of discretely distinct oppositions, each one of which can be thought of as differing absolutely from all others in the paradigm. The foregoing statement, although implicit in some definition of the term <u>phoneme</u>, is not intended as a complete definition. According to Bloomfield (1926), "Such a thing as a 'small difference of sound' does not exist in a language." By one or another of several systems of criteria, all of which perhaps need not concern us here, the sounds of a language are conceived of as being in relation to the paradigm of phonemes of that language. There is, however, one linguistic criterion of phonemic analysis indispensible to the phonetician, namely the concept of <u>phonemic</u> <u>distinctiveness</u> (or <u>non-distinctiveness</u>), usually called <u>phonetic</u> <u>dissimilarity</u> (or phonetic similarity).[2] Unfortunately, a scientifically rigorous definition of "phonetic similarity" has not been proposed in the literature (Bloch, 1941; Austin, 1957). The following list of assumptions is intended in part as an approach to a definition of phonemic distinctiveness arising from phonetic dissimilarity.

Assumptions

Bearing in mind the danger of confusing levels of abstraction in phonological analysis, the following assumptions are made:

Assumption 1. Phonetic behavior is not completely random but partly random and partly patterned (partly predictable).

Assumption 2. Certain kinds of phonetic events are more patterned than others, due both to phylogenetic and to cultural factors. That is to say, certain kinds of phonetic behavior are more predictable than others. It is sometimes suggested, e.g., by Twaddell (1935), or by Bloomfield (1933), that the human speech organs are capable of an almost infinite variety of sounds. A more complete statement would note that although nearly any sound is possible, some sounds are, for purely phonetic reasons,

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[2] An attempt is made here to keep physical (phonetic) and functional (phonemic) nomenclature separate, following Malmberg (1962). See the next chapter.

considerably less likely than others. This phonetic patterning is, of course, in addition to whatever phonemic patterning exists in the language.

Assumption 3. Similarities and dissimilarities within and between sub-classes of phonetic events can be expressed either qualitatively or quantitatively. No _a priori_ advantages attach to either. That expression of phonetic dissimilarity or similarity is best that in the end accounts for all the important differences in the most economical way.

Assumption 4. Dissimilarities in phonetics stated quantitatively can be expressed in any convenient parameter. All measurement in phonetics can be said to be _derived_ measurement, that is to say every quantitative phonetic parameter is an expression of a function of variability in more than one mode, or domain (Campbell). One parameter is chosen in preference to another because it is in some way consonant with some theory of phonetic variability. The price paid for simplicity of parameter might well be an excessive complexity of results.

Assumption 5. More than one parameter is needed to describe all phonetic dissimilarities in the language and no one parameter is useful in describing all phonetic dissimilarities in the language.

Assumption 6. The variabilities in the various parameters are neither constant nor equal. For example, phonetic dissimilarity in a certain parameter is not always equally apparent, but may exhibit differing patterns of applicability, depending on the phonetic environment. Similarly, within the linguistic structure, the relevance of a feature of distinctiveness is often syntagmatically conditioned. Such a feature, being phonemically relevant in some context but being rendered irrelevant in a portion of a particular string, is said to be neutralized in that portion of that string (Trubetzkoy, 1936).

Assumption 7. Of the two or more parameters chosen to describe a certain pattern of phonetic dissimilarity, if one is found to be more useful than the others, then the others are said to be redundant. Such parameters may or may not be related to each other as simple transformations.

Assumption 8. Patterns of perceptual response may be correlated with phonetic (acoustic or physiological) patterns. Negatively stated, no putative pattern of phonetic similarity or dissimilarity can be linguistically useful if it can be shown that native speakers are not responsive to alleged differences in the parameter in question. The person to whom one is speaking cannot respond to a stimulus he cannot perceive.

The import of Assumptions 5, 6, 7, and 8 is that phonetic description need not be total to be useful.

Whereas a phonemic paradigm must be complete, it is held here that under the above assumptions, phonetic description can be carried out eclectically on a portion of the phonetic events in the language, with appropriate note taken of the similarities and differences within sub-classes and between sub-classes of phones.

The portion of the English language to be described in the present experiment was chosen in such a way as to increase the likelihood of maximal phonemic variety. The plan for the present experiment provided for investigation of those vowels least subject to neutralizations. Previous studies indicate that front vowels in closed stressed syllables, before single consonants excluding _-r_, would provide a field sufficiently rich to yield data useful for a phonemic analysis. Further information on the experiment itself will be included in chapter 3.

Phonetic dissimilarity and phonemic distinctiveness

With the above assumptions in mind, satisfactory answers to the following questions will serve to establish working definitions for the phonetic concepts of similarity and dissimilarity, and for the analogous phonemic concepts of non-distinctiveness and distinctiveness.

1. With respect to what phonetic parameters are the sounds in question similar or dissimilar?

2. What are the patterns of phonetic similarity or

dissimilarity?

3. What is the evidence that a speaker is able to perceive and to respond to variability in the parameters in question?

4. What are the phonemic patterns relating features of distinctiveness to each other and to the phonetic patterns?

5. How are the patterns of phonemic distinctiveness best incorporated in a complete phoneme paradigm in such a way as not to obscure any important information about the phonology of the language?

In investigating the front vowels of Midwestern American English, answers to the first two questions will be attempted in this dissertation in an experiment to be outlined in chapter 3. The first two questions are purely phonetic in nature. The third has to do with the relationship between perceptual psychology and phonetics. Important though this area is for the general phonological theory referred to here, the present experiment did not involve the correlation of acoustic data to perceptual data. The fourth question combines phonetics and phonemics. The last question, involving those criteria of phonological analysis that are extra-phonetic, lies therefore beyond the scope of this dissertation. The discovery or devising of a phonemic paradigm involves, moreover, the consideration of all available phonetic patterns, both paradigmatic and syntagmatic.

Plan for the dissertation

The dissertation will consist of five chapters. After the present introductory chapter will follow a chapter on levels of abstraction in phonological analysis. Chapter three will be on the experimental plan in detail, including a discussion of the chosen acoustic phonetic parameters. The fourth chapter will concern the accuracy of the measurements reported in the dissertation. Chapter five will be a report on the results of the experiment, together with an indication of how the acoustic phonetic data presented in this dissertation might be applied in a phonemic analysis of Midwestern American English. Appended material will show the computational program that has yielded the acoustic phonetic results, together with tables of those results. A bibliography, not to be commented on elsewhere in general terms, will include sources that have been useful in the preparation of this dissertation. Items included will relate to the areas of linguistic theory, phonetics, speech perception, automatic speech recognition, measurement theory, and psychophysical scaling. No attempt is made at a classification of bibliographical sources because of a considerable overlapping of categories.

Summary

A rationale for the inclusion of experimental phonetics within the natural sciences and for incorporating phonetic data in statements, on a higher level of abstraction, within the science of linguistics is outlined. A list of explicit assumptions is provided which might govern the mapping of phonetic data onto phonemic descriptions. An understanding of the meaning of phonetic similarity, as properly so called, and of the analogous but by no means synonymous phonemic non-distinctiveness is crucial. A relationship is outlined between acoustic phonetic patterns and phonemic patterns in the solution of a problem in the phonology of Midwestern English vowels.

Chapter 2. Levels of Abstraction

The article by Malmberg (1962) on levels of abstraction in phonetic and phonemic analysis is extended and applied to the problem at hand. Several methods can be devised for isolating levels of phonological abstraction, such as the four levels listed by Malmberg himself. In pointing out that the choice of levels is to some extent at the discretion of the phonologist, Malmberg nevertheless warns his reader of the dangers in a bipartite division into phonetics and phonemics, and against characterizing some of his lower levels as phonetic and therefore completely non-phonemic (223). A progression of successively more functional (i.e. phonemic) levels of abstraction is proposed here, differing in the scope of inquiry, from a single utterance by one speaker on the lowest level to all possible utterances by all speakers of all languages on the seventh and highest level. The seven levels differ from lowest to highest in successively more paradigmatic parsimony, more generalization, more reliance on syntagma, more "hocus-pocus" (Householder, 1952; 1965).

1. On the lowest level of phonological abstraction is the phonetic description of unique phonological

events, limited to the detailed portrayal of a single instance of the utterance of a particular short string of speech tokens. On this lowest level there is no consideration of oppostion between members of a paradigm, for there is no paradigm without generalization. Similarly there is no syntagmatic contrast. The technique of observation and description involves physical measurement by laboratory instruments. The material being observed might be short segments of tape, small portions of spectrograms, or x-ray film. On this level there can be theoretically no correlation between form and function, as differences in function are not yet known and differences in form are just emerging, to appear on the second level. In actual practice, as Malmberg points out, there can be no meaningful description of speech tokens without relation to speech types. This first level is included here merely for the sake of completeness.

2. On the second level of phonological abstraction is comparison between two or more speech tokens as above, from the speech of one speaker, or by extension, from the speech of a small group of speakers. The purpose of description on this level is the collection of data to be used in establishing phonetic equivalence classes. The tokens can be segmented on this level, that is, they can be contrasted with each other so as to show what are strings of events and what are elongations of single events.

At the same time, opposition between phonetic events can be shown. In other words, the tokens can be classed into types. Given enough tokens, a phonetic paradigm can be established for a portion of the speech of a speaker. A complete phonetic paradigm would be an exhaustive list of the types of phonetic events in one variety of speech. The description of the items in the paradigm can be carried out on any appropriate level of phonetic abstraction. Included are all phonetic equivalence classes observable by whatever means. The only requirements on this second level are: that judgements be made, presumably relying mostly on objective measurement, as to the randomnesses and patternednesses of the tokens; that tokens showing the same patterns (i.e. differing only randomly) be classed together; and that all tokens in that portion of that variety of speech be fit into some class. Randomness in phonetics is of two sorts: in the first place the variation between the two events may be so slight as not to be noticed, because of the relative imprecision of the measuring device, because of an organically conditioned low hearing acuity of the listener; and in the second place the observer may notice a particular variation between events, but in an act of personal participation in the observation process, he may deliberately intervene to judge the two events to be just randomly different and therefore equivalent. Of course it is not possible for a phonetician to eliminate entirely this intervention. Even on the lowest level of phonetic abstraction, by the choice and design of instruments and by the particular technique of observation employed, he tacitly arranges to record certain data and to ignore others. It can perhaps be doubted that a phonetician can ever completely set aside his previous phonological and other linguistic experience when he makes phonetic observations. The question is not whether there are phonemic prerequisites to phonetic analysis but how aware the phonetician may be of his intervention, bias, and previous experience.

The phonetic paradigm established on this level is far longer than the inventory of special phonetic symbols customarily used in detailed dialect study unaided by laboratory instruments for analysis. Indeed, on this second level of phonetic abstraction it is best not to think in terms of symbols but rather in terms of detailed descriptions of events accompanied by tables of measurements.

3. The third level of phonological abstraction can be called the level of narrow phonetic transcription of all utterances that occur in a dialect of a language. The large number of types of phones of the second level are replaced here on the third level by the several dozen of practical significance. The phonetic paradigm used for a narrow transcription is limited to an enumeration of

those sounds that the unaided, albeit highly trained, phonetician's ear can distinguish. Various systems of narrow phonetic transcription, such as the alphabet of the International Phonetic Association, are, to be sure, often extended to encompass a variety of possible nuances of pronunciation, depending on phonetic environment, dialect, and style of speaking. No system of discrete transcription can, however, show all differences. At the third level of phonological abstraction the phonetician records what is under the circumstances possible and necessary. The types of phones in the paradigm are on this level the allophones of the language, as applied to a particular dialect.

A narrow phonetic transcription involves quite probably a considerable phonemic bias: the phonetician can only hear what he has trained himself to hear and that training includes the phonemic pattern of his own dialect.

At the third and higher levels of phonological abstraction are the distinctive features, as that term is used by Jakobson, Fant, and Halle (1952). The strategy of distinctive-features linguistics is to procede in the opposite direction from that represented here. Under Halle's Condition 4 (1959: 24), that "the phonological description must be appropriately integrated into the grammar of the language," the process of specification of the segments of the language begins with the sentence. The grammar, according to that school, is a set of instructions for specifying on successively lower levels what general symbols can be replaced by what more specific rules, until the lowest level is reached: that of irreplaceable terminal strings, called segments (i.e. "phonemes") with their boundaries, or matrices of distinctive features. The reason for this difference in linguistic strategy is not pertinent to the problem at hand. One effect of the different approach to linguistics represented by distinctive features should be pointed out however. If, as has been suggested by Halle (1959: 24), the phonology should <u>not</u> include rules for inferring the pronunciation of any speech event, then the field of scientific phonology for a distinctive-features linguist is restricted to the third and higher levels of abstraction, at the very lowest.

4. The fourth level of abstraction in phonology is the level of broad phonetic transcription of all possible utterances in a dialect of a language. The term "broad transcription" is admittedly not amenable to exact definition. Daniel Jones, in his <u>Outline of English Phonetics</u> (pp. 51, 332), indicates that the aim of broad transcription is to "represent only the phonemes of a language, using for this purpose the minimum number of letter shapes of simplest Romanic form ..." As the meaning of "broad transcription" depends then on the meaning of "phoneme", and as in the appropriate passage in Jones' <u>The Phoneme</u>, that term is explained rather than defined (pp. 7, 8), we are

left with the feeling that "narrow" and "broad" are relative terms, whose utility is governed by the practical application to which they are put. Jones follows the tradition of Sweet (1877), to whom he makes acknowledgement.

Despite its relative imprecision, the term "broad transcription" is clearly seen to lie on a higher level of abstraction than "narrow transcription", both in terms of paradigmatic parsimony and in terms of scope of inquiry or application to a variety of possible utterances in the dialect (Jones, 1955: 13fn, 51 fn).

5. If, in spite of Malmberg's caution (1962), a division were made between phonetics and phonemics, that division would be at the fifth level of abstraction. In differentiating between "broad phonetic" and what is referred to here (reluctantly) as "narrow phonemic", there is a danger of unnecessary proliferation of terms. In practice the resultant paradigm and syntagmatic rules might well be similar in size and scope. Indeed, British phonologists often use the terms "broad phonetic" and "phonemic" synonymously (Jones, 1956: 332). There is, however, an important theoretical distinction to be drawn between phonology on the fourth and on the fifth levels. The term <u>phoneme</u> is usually interpreted by linguists in America and on the European continent as a set of relationships: invariant oppositions and contrasts, in other words a theoretical construct, an abstraction, even a fiction.

Phonetics on the other hand, by which is included for the present purpose much of what is covered in Jones' The Phoneme (1950), deals with sounds and how they are classified into families, whether they are "principal members: or subsidiary members." (The Phoneme: 8). The term "phoneme" as it has been borrowed in America by psychologists and others outside the field of linguistics tends to mean a set of relationships (fifth level). Both phonetics and phonemics deal with form and function, but in phonetics the emphasis is on formal differences, whereas in phonemics it is the distinctions in function that are emphasized. To generalize, at some risk as noted above, phonetics deals with concrete sounds, phonemics with abstractions about systems of distinctions. This dissertation is concerned with the (phonetic) description of concrete sounds.

Phonemic systems may differ, as do phonetic systems as well, with respect to paradigmatic parsimony and scope of inquiry. What is meant here by "narrow phonemic" is a system with a relatively larger paradigm. The scope of inquiry is limited to just those utterances attested in a particular language. Examples are the systems of Kurath (1961) and Fries (1945) for English.

6. The sixth level of phonological abstraction is the level of "broad phonemic" systems whose scope of inquiry is all possible utterances in a language, including dialectal and stylistic variations. The relatively greater

paradigmatic economy of such systems is offset by less economy of syntagma. Such a system may be constructed on the basis of essentially the same set of postulates or other general theoretical considerations as a narrow phonemic system for the same language. The difference in such a case might be attributable to a different strategy for the application of those general considerations. Another difference between a phonemic system of the fifth level and one of the sixth level is that as distributional criteria, important as they may be on lower phonological levels, take on even more importance as the level of abstraction increases. Congruity of pattern tends to apply more to syntagmatic pattern on the sixth level than it does on the fifth level.

As Halle points out, it is always possible to reduce the paradigm to a limit, in the trivial case, of two "phonemes." (1959: 22). Each paradigmatic reduction imposes more syntagmatic elaboration and less concrete phonetic detail: in sum, more abstraction.

7. The seventh level of phonological abstraction is the highest level of linguistic analysis that relates sound form to sound function. The scope of inquiry is all possible utterances by all speakers of all languages. Glossematics represents the most abstract approach to phonology, followed closely by the Prague school, as exemplified by Trubetzkoy's Grundzüge (1939) and its outgrowth in

Jakobson's distinctive-features analysis (Jakobson, Fant, and Halle, 1952). The subtitle of Hjelmslev and Uldall's "Outline of Glossematics," (A Study in the Methodology of the Humanities with Special Reference to Linguistics), would indicate the high level of abstraction of that school. Uldall, in referring to glossematics, explains that

> The algebra we have presented here, in Part I, is universal, i.e., its application is not confined to materials of any particular kind, and it is thus not specifically linguistic, or even humanistic, in scope or character, though our main purpose in designing it has been to provide for the description of linguistic and other humanistic materials. (Hjelmslev and Uldall, 1957: 86)

Chomsky and Halle indicate that the level of abstraction of their kind of grammar is high enough to encompass sentences, but no higher (1965: 97-98).

The foregoing account of levels of abstraction in phonology has not included Pike's school of linguistics. Tagmemics is designed to handle linguistic (or other behavioral) relationships at all levels of abstraction.

> The activity of man constitutes a structural whole, in such a way that it cannot be subdivided into neat "parts" or "levels" of "compartments" with language in a behavioral compartment insulated in character, content, and organization from other behavior. Verbal and nonverbal activity is a unified whole, and theory and methodology should be organized or created to treat it as such (Pike, 1954: 2).

The strategy of tagmemics is to specify the level of abstraction at every point in the description of the language. It is thus unnecessary to consider tagmemics exclusively in connection with any one level of phonological abstraction.

The attempt has been made here to outline one possible scheme for characterizing phonological descriptions with regard to their differing levels of abstraction. This scheme has taken into account differences in scope of inquiry, in paradigmatic economy, and in generalizability. The present dissertation is seen as an experiment primarily on the second but also on the third level of phonological abstraction: the level of detailed description of a small number of speech samples and the level of narrow phonetic transcription of a dialect. The purpose of this brief note on phonological abstraction has been to avoid the kind of error Malmberg has reference to when he points out that

> Numerous mistakes in traditional phonetics have been due to a confusion of levels of abstraction. The scholar is free to choose the levels he prefers and finds suitable for his purpose. No level is scientifically better than any other. The choice of level is never a methodological mistake. The confusion of levels always is (1962: 241).

Chapter 3. The Experiment

In this chapter will be discussed the corpus under investigation, the parameters measured in the corpus, and the techniques of measurement and computation.

The Corpus

On a broad phonetic level of abstraction, the utterance of a closed monosyllabic word of the type under investigation in the present experiment is considered to have a certain phonetic structure, as follows. Each such word is realized as a *syllable* within Hockett's meaning of the term (1955: 51-64, 223). Each syllable has a *vocalic nucleus*, which is a phonetic event or short string of phonetic events, probably not more than two, namely a vowel alone or a vowel followed by a semi-vowel or semi-vocalic offglide. It is not known that any phonetician proposes a phonetic structure more complex than indicated above. The terms *vowel*, *semi-vowel*, and *semi-vocalic offglide* are not defined here, for the differentiation of those terms is among the purposes of the experiment. Rather, a few illustrative examples are given below and the complete corpus is appended.

The nuclei of the syllables in question are followed in each case by a simple coda (Hockett, 1955:63), a single phonetic event or short string of phonetic events, usually symbolized in broad phonetic or in phonemic transcription by a single consonantal symbol. The term _consonant_ is not defined here, for it is not known to be the subject of pertinent controversy among phoneticians and the definition is not crucial to the present experiment. Any current phonetic definition of _consonant_ can be applied in this dissertation, provided that the consonants are understood to be several and mutually exclusive with the vowels.

Most of the syllables in the corpus have a simple onset consisting of a single consonant, including a single affricate, or a single semi-consonant (i.e. the resonants _l_, _m_, _n_).

Phonetic Characteristics

A cursory examination of sound spectrographs of speech, or any experience with the splicing of short (i.e. sub-syllabic) segments of recorded tape would be enough to convince any linguist that on a lower level of phonetic abstraction than that indicated above, it is usually quite difficult and often indeed impossible to demarcate the stream of speech into syntagmatically discrete, sequentially segmentable phones. For example, in investigating a closed syllable, one cannot choose a point in time before which there is no foretaste of the coda and after which

there is no remaining trace of the nucleus. There is instead usually a span of time, extending in extreme cases over most of the length of the syllable, during which the nucleus and coda are smeared together.
This span of time, covering transitions, glides, and diphthongs, was the subject of a study by Lehiste and Peterson (1961). Although the results offered here agree in general with Lehiste and Peterson, the methods are different.

In considering the following words: (1) beat, (2) bit, (3)bait, (4)bet, (5) bat; or (1) meat, (2) mitt, (3) mate, (4)met, (5) mat; or (1) seal, (2) sill, (3) sail, (4) sell, (5) Sal, several acoustic phonetic characteristics can be observed. It is assumed that there are always several factors present, more than one of which might operate to distinguish two vowel sounds and that the sounds are relatively similar with respect to certain factors and relatively dissimilar (on the second level of phonological abstraction) with respect to other factors. It is assumed that the following is an exhaustive list of phonetic characteristics which distinguish the front vowels in Midwestern American English: (1) height, (2) frontness, (3) aperture, (4) diffuseness, (5) length, (6) transition, (7) upward glide, (8) downward glide, (9) pitch, and (10) loudness. All of the above characteristics have been found to play a role in distinguishing some of the five nuclei exemplified from some of the others. A major part of the experiment was the attempt to combine several of the listed characteristics into a relatively simple set of acoustic parameters on the second level of phonological abstraction. Although it has been determined that for vowels in general the specification of the first three formants is highly advantageous, for the restricted corpus in question it was considered desirable to be able to investigate just the first two formants. For the kind of detailed examination undertaken, it would have enormously complicated the treatment of the data to have included the third formant. The computation was in three dimensions: frequency of the first formant; frequency of the second formant; and time.

Considering all but the last two of the ten phonetic characteristics listed above, it can be shown that the frequencies of the two formants and their variations in time can account for all the phonetic differences as indicated briefly below, and in greater detail elsewhere. Care must be taken to avoid confusion of the phonetic characteristics outlined herein with the distinctive features of Jakobson, Fant,and Halle. In particular, <u>diffuseness</u>, is here given a narrower definition than in the <u>Preliminaries</u> (1952: 27). The distinctive features are moreover to be associated with phonological abstraction on the third and higher levels. The phonetic characteristics are described here on the second level of abstraction. The following account is intended to show how the phonetic characteristics are related to each other and how they vary with respect to each other.

1. Height, as it is often called, or tongue height, means primarily how high the tongue is placed in the mouth. In acoustic terms it is inversely associated with the frequency of the first formant: the higher the tongue, *ceteris paribus*, the lower the first formant.

2. Frontness means how far toward the front of the mouth the tongue is extended. In acoustic terms, frontness is associated with an elevated second formant: the more toward the front of the mouth the tongue is placed, *ceteris paribus*, the higher the second formant frequency.

3. Aperture is approximately equivalent to how wide (or how narrow) the oral opening is. Aperture depends on the two foregoing characteristics: the higher (and less importantly, the more toward the front of the mouth) the tongue is placed, the smaller the opening. In terms of the acoustic phonetic parameters, a small value for aperture (cf. small opening) is associated primarily with low first formant frequency and secondarily with high second formant. The precise definition of aperture appears in its own section in this chapter. The following figure (Figure 1) shows the relationships between changes in height, frontness, aperture, and the frequencies of the two formants.

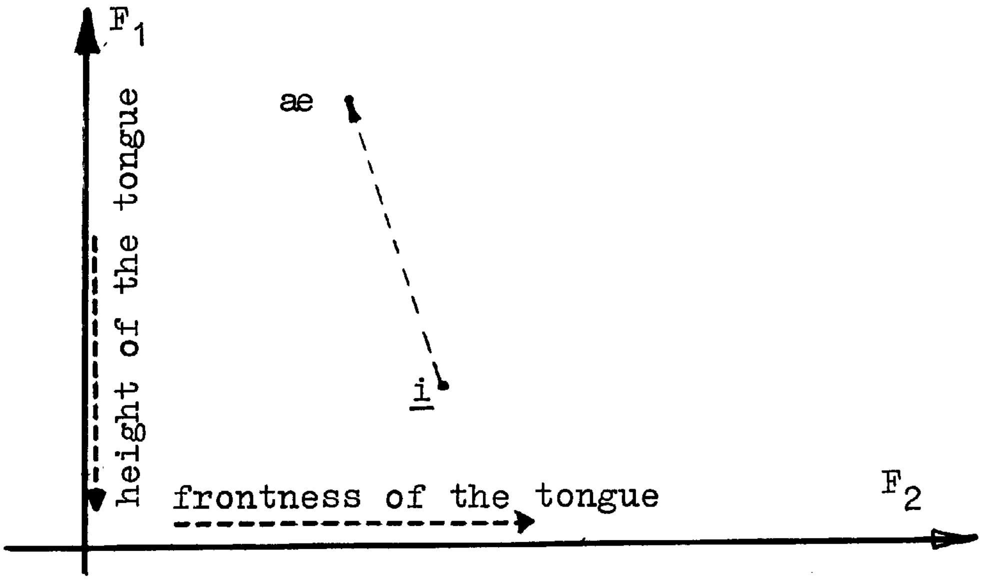

Figure 1. Change in aperture related to changes in other parameters

4. Diffuseness is a purely acoustic term that refers in this dissertation to the relative separation between the two formants. Front vowels tend to be more diffuse than back vowels. High front vowels are more diffuse than low front vowels. The technique of measurement of diffuseness is explained in the section on diffuseness.

5. The length of a vowel means its duration in time. What is often referred to as a "long vowel" tends to last longer than a so-called "short vowel". This is not necessarily the case with phonemically short vowels.

6. Transition is a set of specific changes in the first or second or both formant frequencies from a pattern characteristic of a vowel to or toward a pattern characteristic of a following consonant.

7. Upward glide is any one of a set of specific patterns of decrease in first formant accompanied by a slight increase in second formant frequency.

8. Downward glide is any one of a set of patterns of increase in first formant or decrease in second formant frequency, or both.

The details of the patterns of transitions and glides are included in the chapter on results.

It is, to be sure, known that the high front vowels tend to be less intense (perceptually speaking, weaker) and of higher fundamental frequency (perceptually of higher pitch) than the low front vowels (Lehiste and Peterson, 1959a; Peterson and Barney, 1952). In this dissertation consideration has not been given to intensity and fundamental frequency, not because their contribution to vowel discrimination is being denied, but because it was intended that the complex dynamic relationships of the first two formant frequencies be investigated intensively alone.

As can be seen in Table 1, page 59, the test words were chosen with a view toward maximizing the number of minimal pairs, triplets, and the like. The 180 different words of the corpus were arranged in nine lists of 20 words each. In so far as possible, the lists were balanced in such a way that (a) each nucleus of the five different types was represented approximately equally in all lists, and (b) each consonantal context, both onset and coda, was spread over as many lists as possible. This meant that it was unlikely that a minimal pair would occur within a list. Each list was permuted and replicated eleven times, randomly with one constraint: adjacent words did not include vowels of identical type.

For the kind of intensive study envisioned it became apparent during the spectrographic analysis that the amount of data would have to be reduced in one of two ways: (1) the number of sample tokens of each word type would be limited, or (2) the number of types of different words would be limited. The first alternative would have reduced the number of consonantal contexts that could have been included in the corpus and would, moreover, have jeopardized the chance of discovering the acoustic patterns within a given word type. As it happened, the extent of variation within each word type was considerably greater than had been expected. The decision was therefore made to limit the number of types of different words and to study them in greater detail. The purpose of the dissertation was not to discover and describe all patterns of all parameters in all words of a given context, but to investigate the typical manifestation in selected words of the parameters in question. Accordingly, a selection was made from six of the eleven forms (i.e. eleven replications) of each list and these words were recorded on an Ampex

350 tape recorder at 15 inches per second in a quiet recording room. The tape was then monitored and transcribed by hand twice at intervals of two weeks. The two handwritten transcriptions were then compared with the original typewritten script. Only those samples were marked for subsequent analysis that were on both monitorings perceived as good examples of the intended words. In this way, as was hoped, qualitative variations between words of identical types would be minimized. A few words were for the same reason eliminated from the corpus later when the samples were monitored from the sound spectrograph. As an additional means of minimizing variations in the data, all speech samples used were spoken by one person, the author.

A total corpus of 478 words of 95 different types was analysed in the broad band condition using the Communication Sciences Laboratory sound spectrograph. The upper limit of frequency was adjusted for each word during analysis so that in so far as possible the full four-inch spectrogram width could be used for a frequency band-width comprising the energy in and below the first two formants. The performance of the sound spectrograph was quite reliable for the formant-structure problem under investigation.[1]

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[1] At times during the several months spent on spectrographic analysis, minor, not intolerable, instabilities would appear in the equipment, which were reflected in the

Measurement

Each word of the list of words marked for analysis was identified on the spectrogram and the first and second formants were traced directly in pencil throughout the entire duration of the vowel-formant structure portion. This meant that a portion of the adjacent consonants might be included. At eighth-inch intervals, parallel vertical lines were drawn perpendicular to the base line through both formants, as illustrated in the sketch above.

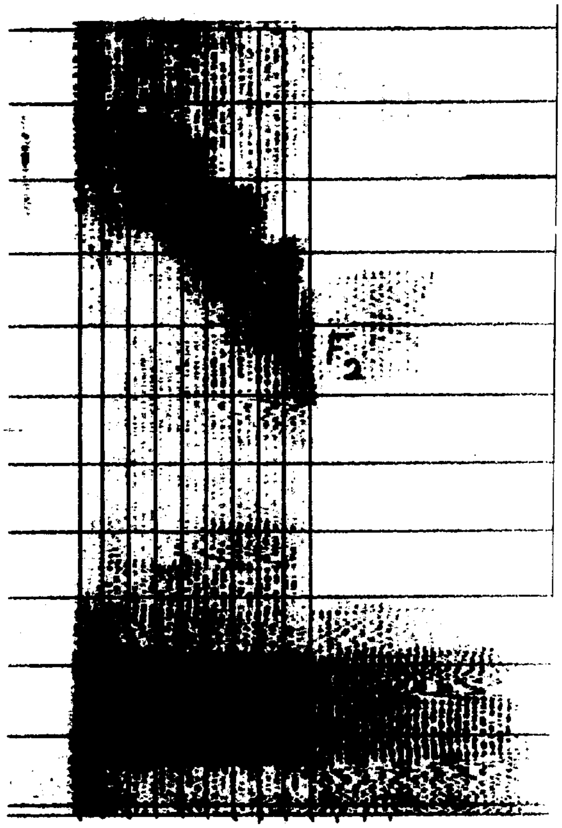

Figure 2. Sound spectrograph of the word 'pin'

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slightly reduced clarity of voiceless fricative consonants. The zero frequency base-line was not always properly marked, but by using the crystal-controlled frequency calibration marked individually on each spectrogram, it was always possible to extrapolate the base-line accurately enough.

For each increment in time two measurements were recorded, one for each formant, with a sensitivity of ±0.001 inch, using a set of machinist's dial calipers. The calibrations and tolerances of the entire measurement process will be treated in Chapter 4. The scale factor of the ordinate (i.e. the rate in cycles per second per inch at which the sound spectrograph was set to scan, nominally 583, 834, or 875 cycles per second per inch) was noted in the data worksheets, along with the identification of the consonantal context within which the vowel occurred, the serial number, and the number of the list from which it was recorded. All of this information on the data worksheets was then punched onto tabulating cards; at least two cards were required per sample word. The cards were then checked for accuracy and processed by the digital computer.

Logarithmic scale

The kind of computation undertaken in this dissertation required a standard unit of frequency difference in terms of which changes in formant frequency or relationships between formant frequencies could be expressed independent of absolute frequency. Ideally, an appropriate psychophysical unit would have been adopted, had there been available a psychophysical law for converting frequency in cycles per second (the unit of the sound spectrograph used)into perceptual formant pitch. The precise psycho-acoustic relationship between frequency and pitch, even for the simple (pure sinusoidal) stimuli studied so far by psychologists, is very complex. S. S. Stevens, who has shown that the best general psychophysical law for <u>prothetic</u> ("quantitative") perceptual continua is a power function (1957), does not offer a simple formula for transforming frequency into pitch. Instead, he characterizes pitch and other such "qualitative" psychophysical continua as <u>metathetic</u>, that is to say pitch is not additive as is loudness, heaviness, brightness, and duration (Stevens, 1958, 1959) but qualitatively substitutable.[2] Nevertheless, the evidence for an essentially logarithmic relationship between pitch and frequency, at least within a restricted frame of reference, is quite compelling. The standard musical units of pitch relationship, namely the octave and the semitone, are logarithmic units.

Despite the contributions of Flanagan and of the Haskins Laboratory psychologists, evidence on the pitch of complex tones (e.g. speech) and on the pitch of non-fundamental (i.e. harmonic) tones such as vowel formants, is sketchy. In choosing a unit for reporting frequency

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[2] Stevens' law is that the psychophysical magnitude of a stimulus is equal to some constant multiplied by the physical magnitude of the stimulus raised to some constant power, The classic Weber-Fechner law (Fechner: 1860) is that to the logarithm of the intensity of the stimulus. The pitch scale offered by Stevens and Volkmann (1940), is too cumbersome to have been used for this dissertation.

differences the decision had to be made to: (a) use a logarithmic unit; (b) devise a rationale for using frequency in cycles per second; or (c) use a psychophysical formant pitch scale. As a formant pitch scale for complex tones is not known to exist, and as there was no compelling reason (other than a slight convenience, to be discussed below) for using cycles per second, the decision was made to use a logarithmic scale for treating differences or changes in formant frequency. Measurements in inches from the spectrograms were to be converted directly into this logarithmic unit in the computing process, without any reference to cycles per second. Any logarithmic value could however be uniquely recovered as cycles per second by reference to a table.

One logarithmic base would have been just as convenient as another for this purpose. Rather than 2.718, or 10, or some other base, the base two was chosen as having somee kind of "psychological significance". The reported data could then be conceptualized at certain check points in the scale by referring them to the equal tempered scale of musical pitch. The frequency of the first formant, for example, was reported as octaves and fractions of octaves above 55 cycles per second, which happens to be the sound of the open A string of the string bass. Any integral number of octaves above 55 cycles per second would be some tone A of the equal tempered scale. The one place to the left of the decimal point, the integral portion of the logarithm which expresses the number of whole octaves is called the characteristic. The fractional portion, the three places to the right of the decimal point which express the fractional part of the octave, is called the mantissa. The reason for using three place mantissas is discussed elsewhere in connection with the account of the measuring process.

Parameters

As has been suggested earlier in this chapter, all or very nearly all of the information required in the identification of Midwestern American English front vowels in context is contained in the frequencies of the first two formants. DeGroot (1931) was the first to show the similarity between an F_2 versus F_1 logarithmic (in DeGroot's graphs, musical scale) plot and the kind of traditional articulatory vowel paradigm that goes back at least to Hart (1570). It is not known that an attempt has until now been made to write a mathematical expression relating the vowels of a particular series. One possible reason phoneticians have not concerned themselves with this task might be that there has not been a usable unit of frequency difference, such as that proposed here. In the search for appropriate acoustic phonetic parameters the attempt has been made to establish a connection between the qualitative distinctions of classic articulatory phonetics and phonetic measures, secured where appropriate with the aid of automatic computing devices, of an acoustic nature, on the second level of phonological abstraction.

Aperture

For one of these parameters, here called aperture, a recent description couched in well established articulatory terminology, is given by Malmberg.

> En phonétique traditionelle, une voyelle est dite ouverte ou fermée selon que la distance entre le point le plus élevé du dos de la langue et le dit point d'articulation est grande ou petite. La fermeture est maxima, si le rétrécissement du canal buccal se trouve juste à la limite de ce que permet une articulation vocalique. Au moment où cette limite est dépassée, l'articulation devient consonantique en donnant lieu à un bruit. Dans les schemas vocaliques de type traditionnel, les notions de fermeture et d'ouverture sont liées à l'articulation linguale et sont par conséquent synonymes de position haute et basse, respectivement, du dos de la langue (Malmberg: 1959, 49).

The search is for an acoustic parameter that on the second level of phonological abstraction matches the articulatory continuum of fermeture/ouverture. The front vowels are conceived here in a first approximation as steady-state points in the first quadrant of a two dimensional metric space whose rectangular coordinate axes are as follows: The ordinate (Y) is the ratio of the frequency of the intensity peak[3] of the first formant to the arbitrary reference frequency of 55 cycles per second, the ratio being expressed as octaves above 55 cycles per second. The abscissa (X) is the ratio of the frequency of the peak of the second formant to the arbitrary reference frequency of 220 cycles per second, expressed as octaves above 220 cycles per second. Corresponding to any theoretical steady-state vowel there would be a unique point in that two dimensional space. The notion of phonological opposition implies two such points that are different with respect to first or second format, or both. A parametric notion of phonology implies moreover a continuum between two points, for example between some kind of extreme points. A quantitative parametric phonology implies measurement in that continuum. It is held here that any distance, oblique or otherwise, within such a logarithmic space is itself logarithmic.

To illustrate the concept of steady-state aperture, referring to two hypothetical steady-state vowels, i and æ, the pythagorean distance, A, between them in octaves is given here with reference to the figure on the next page.

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[3] The peaks of the formants were taken to be the blackest regions of the formants, or, in cases of rather uniform blackness, the centers. All spectrograms were of the broad band, frequency versus time type.

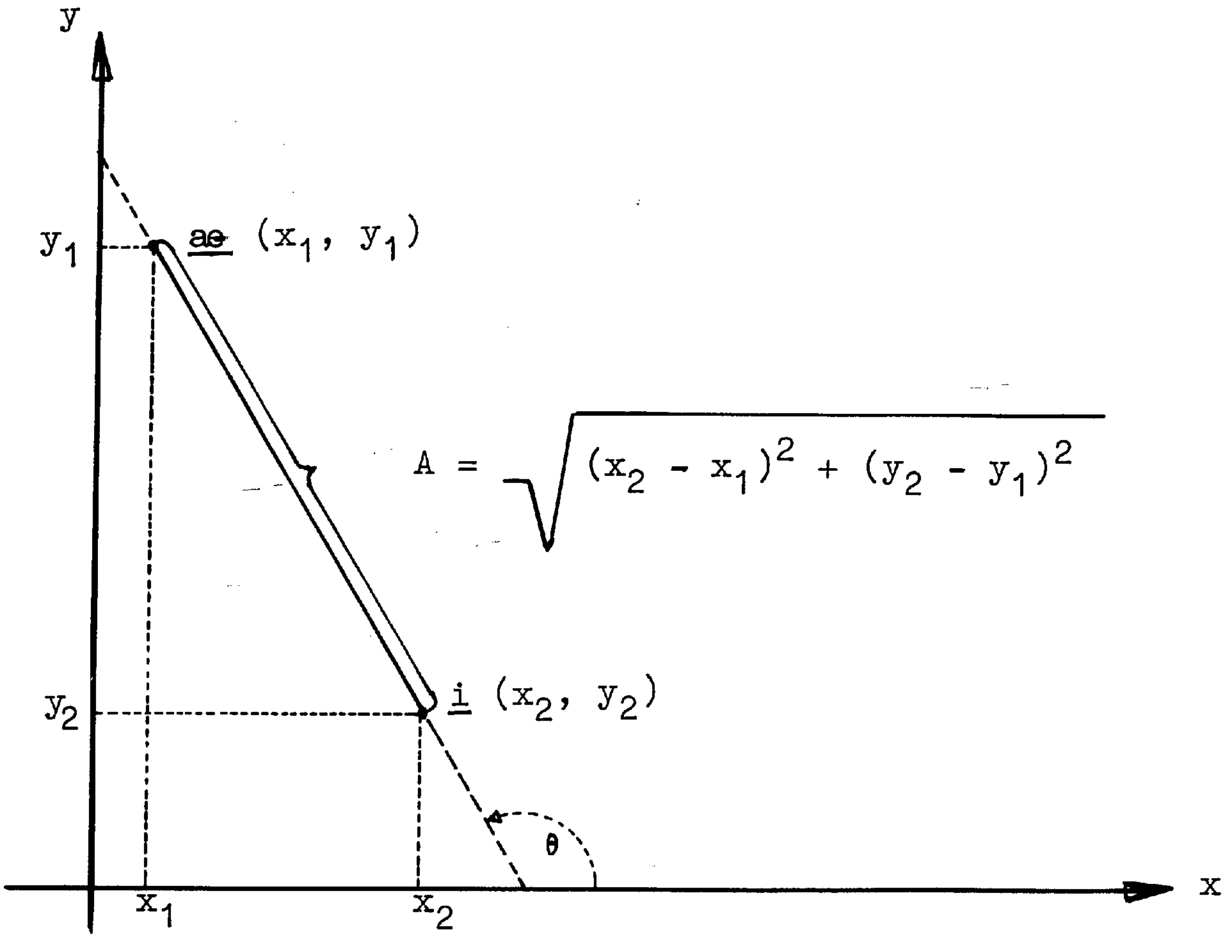

Figure 3. Steady-state difference in aperture

where X is the ratio in octaves between the experimental point for the second formant and the arbitrary reference point for the second formant (220 cycles per second), and Y is the ratio in octaves between the experimental point for the first formant and the arbitrary reference point for the first formant (55 cycles per second).

Such an aperture line between two points, i and ae has two degrees of freedom, expressed in this dissertation as the slope and the Y intercept. That is to say any aperture line is uniquely determined by a specification of both: (1) the angle, Θ, made with the X axis by the extension downward of the aperture line;

and (2) the length of the segment of the Y axis subtended by the extension upward of that line.

A portion of an aperture line, for example the portion covering the range of steady-state empirical values of part of the experiment, is called an aperture line segment. The endpoints of such a static aperture line segment correspond to the least and the greatest values for aperture in a given set of data, for example between i and æ. The position of each of the two endpoints is fixed by the coordinates in F_2F_1 space (i.e. by the specification of the two formant frequencies for i and the two formant frequencies for æ). As will be shown, the location of any static point, say i, in F_2F_1 space depends on the consonantal environment in which the vowel occurs and the point in time within the duration of that vowel, (to say nothing of the age, sex, dialect, etc. of the speaker). For a given speaker there is consequently a family of front vowel aperture lines corresponding to the different phonetic environments of those vowels. The endpoints in each case would be in paradigmatically extreme vowels of each given set of data, for example the vowels i and æ.

If a set of utterance tokens of a certain word type are plotted according to the first versus second formant frequency in octaves of the vowels in those words, there will result a scatter of points characteristic of that vowel in that context, as shown in figure 4.

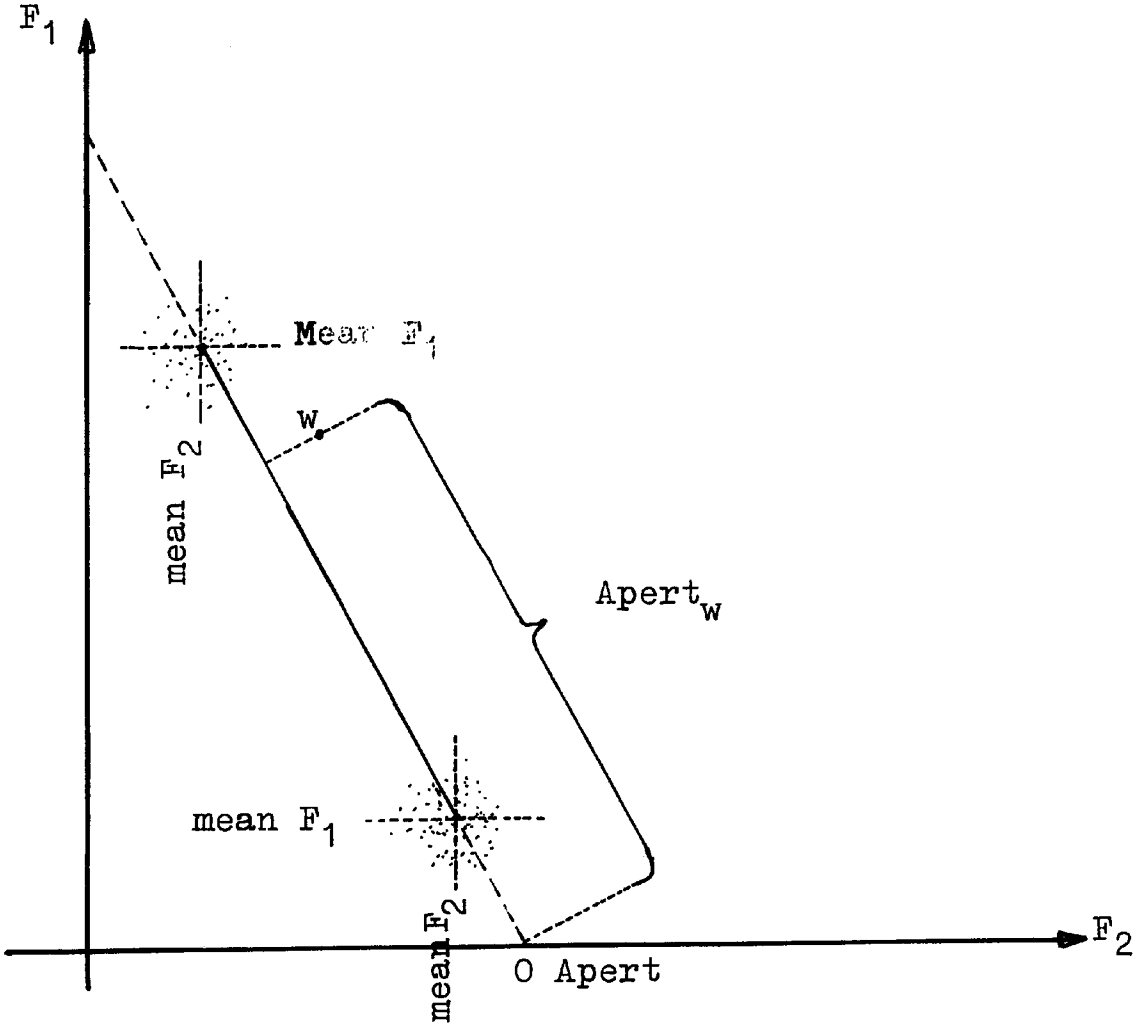

Figure 4. Empirical, context-determined aperture

The centroid of the scatter can be determined in a variety of ways, in this dissertation by finding the point of intersection of the arithmetic mean of all abscissas with the arithmetic mean of all ordinates. The centroid is an average of points characteristic of a certain vowel in a certain context. If the centroids of the paradigmatically extreme points i and ae are chosen as the endpoints of an aperture line segment for a certain consonantal context, any point, w, (as shown in Figure 4), lying along or near that line can be said to have an aperture value equal to the distance between that point on the line (or its perpendicular projection onto the line) and some other point, an arbitrary reference point on the extension of the line segment. All vowels in a given context can in this way have assigned to them an empirical aperture value which can be compared with aperture values of other vowels or arbitrary reference vowels in the same context.

For each of the 41 consonantal contexts of the corpus, the computation program called for a determination of (a) the slope of the empirical aperture line, (b) the intercept of the empirical aperture line, and (c) the aperture values for each measured instant in time for each sample of each context. The empirical aperture values for a particular context were computed on the basis of the slope and intercept determination for that particular context.

It had been predicted that the computation of the individual context-determined empirical aperture lines and aperture values would not succeed in all cases. The fact that computation failed is in itself significant for those phonetic contexts in question, and will be discussed in detail in Chapter 5. In general, failure of the computer to produce aperture values for all contexts was a consequence of three stringent constraints inherent in the computation program: the paradigmatically extreme samples had to be in fact quite disparate acoustically; variation along the hypothesized aperture line had to be greater than variation perpendicular to it; and random variation had not to obscure patterned variation.[4] Thus it was necessary to specify a standard aperture line, with respect to which all aperture values for all samples could be determined. The problem was to find a line in terms of which all aperture values for all 41 contexts could be measured, such that the minimum positive aperture values were minimized, the maximum aperture values were maximized, and the range between the two was maximized. For selected contexts, values were computed for arithmetic averages of the slope and of the intercept, weighted in each instance according to the number of samples in that context. In finding the standard aperture line, only those contexts were selected that met the following conditions: (1) the slope was negative and the intercept was positive; (2) the paradignatically extreme vowels <u>i</u> and <u>æ</u> were amply represented in that context; (3) the range of variation in computed aperture values was low, that is within approximately 0.5 octave, within and between words of the same type; (4) the contexts were

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[4] In general the result of failure to compute satisfactory aperture lines and aperture values was manifested either in a positive slope rather than negative, or in a negative intercept rather than the hypothesized positive intercept, or in absurdly high or low values for slope, intercept, or aperture.

symmetrically obstruent, that is, they contained stops, fricatives, and affricates only, in both onset and coda, and did not contain _l_, _r_, _m_, or _n_; and (5) the computed aperture values were not negative. Using these criteria for selection, a standard aperture line was computed, based on arithmetic means of 764 values for aperture appearing in a total of 51 samples of words from the following context sets: _keep/cap_, _peek/pack_, _piece/pass_, _peach/patch_, _seed/sad_. The averages obtained in this way were the slope and intercept of the standard aperture line, which was then used in computing the aperture values throughout all samples in the corpus.

Dynamic aperture

One object of the experiment was to determine the nature of the patterns of qualitative change, including consonant-to-vowel transition, vowel-to-consonant transition, upward glide, downward glide, and diphthongal off-glide, occurring within and adjacent to the nucleus of a word. For this purpose tables were computed and graphs were plotted on the computer showing the dynamic patterns of aperture change throughout the vocalic and quasi-vocalic portion of each word inclusively, liberally encompassing in most cases a substantial portion of the consonant. For each 1/8 inch horizontal distance on the spectrogram, equivalent to 21.75 milli-seconds in time, an aperture value was computed, tabulated, and plotted. The resultant characteristic dynamic aperture patterns are discussed in a later chapter.

Diffuseness

A striking characteristic of vowels as seen on sound spectrograms is the relative closeness or relative distance between the first two formants. This characteristic observable on the second level of phonological abstraction is included among the factors contributing to the distinctive feature of compactness/diffuseness (Jakobson, Fant, and Halle: 1952, 27). As has been previously mentioned above, the distinctive features do not apply to the first two levels of phonological abstraction. For the computation program used for this dissertation, diffuseness was expressed simply as the difference in octaves between the two first formants. Values were obtained, tabulated, and plotted for all measured instants in time for all samples in the corpus, as with aperture. The characteristic dynamic patterns of diffuseness are discussed in a later chapter.

Program

A MAD program[5] for computing the quantities

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[5] MAD is an acronymic abbreviation for Michigan Algorithmic Decoder, the name for a computer language developed at the Univsity of Michigan.

discussed above was written by the author's son, James A. Reeds III, and was used in several stages for securing the necessary results. The first stage, after the elimination of errors in the data, was the computation of empirical slopes and intercepts of aperture lines for all contexts. Using the results of this computation, a standard aperture line was determined and the entire computation problem was performed again. The possibility of computational error is discussed in the section on measurement theory. The specific results relating to acoustic phonetic patterns are discussed in the chapter on results. In this section will be listed the formulas used in the computation process. A complete listing of the MAD program is appended, together with a discussion of the derivation of the formula for aperture.

The values of the two formants is given by the formulas

$$x = w \ln \frac{(F_2 + .019)z}{220}$$

and

$$y = w \ln \frac{(F_1 + .019)z}{55} ,$$

where w is the modulus for converting natural logarithms with the base e to logarithms with the base 2. This constant modulus is the reciprocal of the logarithm to the base e of 2, and is equal to 1.44269. Z is a scale factor, typically 583, less often 834 or 875, the number of cycles per second per linear inch of the ordinate scale, depending on the setting of the sound spectrograph for frequency scanning. The independent variables F_1 and F_2 are the ordinate distances in inches, measured from the sound spectrograms, between the base line (= 0 cps) and the intensity peaks of the first and second formants at any one instant in time. F_1 and F_2 correspond to frequencies in cycles per second. 0.019 is a systematic correction factor for an error in the measurement instrument used. All values were read systematically too low by that amount, so 0.019 inch was automatically added to all readings. The arbitrary reference values 55 and 220 are the zero points for frequency ratios involving the first and second formants. Using different zero points for the two formants, in this case exactly two octaves apart, made it possible to compress the graphs of the first two formants for more convenient reading.

The formula for the diffuseness at any one instant in time is

$$d = w \ln \frac{F_2 + .019}{F_1 + .019},$$

The formula for aperture is

$$a = \frac{-\frac{b}{m} - x - ym}{\sqrt{m^2 + 1}} = 1.2350 - .3104x + .9506y,$$

where m is the slope of the standard aperture line and is equal to -3.0625, and b is the intercept, 12.1845. Both the standard slope and standard intercept used for the final stage of the computation were derived from empirical values obtained in previous stages of computation. The details of this process of deriving the standard slope and intercept are discussed in the chapter on results.

Summary

A corpus of monosyllabic words having a certain general shape is described, illustrated and listed. The words have a front vowel, followed always by a single consonant and preceded nearly always by a single consonant. Using the sound spectrograph, the first two formants were accurately measured as many as 18 times during each word. Computations were made on these measurements to derive certain acoustic phonetic parameters characteristic of the phonetic patterns under investigation on a relatively low level of phonological abstraction.

Chapter 4. Accuracy of measurement

A consideration of the various factors involved in the measurement process is attempted here. The theory of measurement used calls for an accuracy specification in the final results of one doubtful place of decimals. In other words an estimation is sought which is no more than ten times the accuracy of the place of least count of the last element (T. N. Whitehead, 1954). As it had not been known at the outset what magnitude the various errors would show, the identification of the first truly doubtful place was postponed until the measurement process was completed. This meant that some measurement elements had excessive sensitivities ascribed to them. All of the conceivable sources of measuring error are taken up individually below. They are then related collectively to human perceptual acuity for formant frequency.

Tape recorder

The frequency fidelity of the Ampex model 350 magnetic tape recorder was not seriously questioned. A possible source of unreliability would be short period errors (flutter and wow) in tape drive speed. Any resulting formant frequency distortion would of course be exactly proportional to fundamental frequency distortion, which was checked in the following way. A highly stable 200 cycle frequency standard was recorded onto the tape through a microphone at the beginning and at the end of each recording session. Spectrograms were made of this sound using a pulse shaping device designed to give sharp spikes extending throughout the speech range. In this way a record was made of the cumulative frequency error of the tape recorder and of the sound spectrograph recording mechanism. This cumulative error was not detectable. The appropriate Standard of the National Association of Radio and Television Broadcasters, section 2.40 (1953) specifies ±0.2% (equivalent to 0.0029^{ovo}) frequency error.

The intrinsic magnetic recording and reproducing part of the sound spectrograph was checked for frequency fidelity as above and also independently by feeding the 200 cycle pulse standard directly into the sound spectrograph without using the extrinsic tape recorder. As was to have been expected, there was again no detectable frequency error. From time to time a distressing discontinuity appeared in the recorded image on the sound spectrograph. This gap was eliminated in each case by simply recording the sample again.

Other sources of error are considered below. The magnitudes are all reported as positive errors in octaves at 300 cycles per second and 2000 cycles per second. Negative errors, with one exception, would have been equally likely. This one exception was the possible error introduced by backlash in the dial calipers. As will be seen below, however, this would have been in any case a negligible source of error.

Spectrograph marking

The sensitivity of the sound spectrograph marking was a potential source of error due to lathe backlash. This error was measured at as much as ±0.05 inch (equivalent to $\pm 0.13^{\mathrm{ovo}}$ at 300 cycles or $\pm 0.021^{\mathrm{ovo}}$ at 2000 cycles). Fortunately the frequency was continuously checked by the intrinsic crystal controlled frequency scale marked directly on each spectrogram individually.

Pencil tracing

Successive tracings of different spectrograms of identical recordings were within ±20 cycles per second, equivalent to $+0.093^{\mathrm{ovo}}$ at 300 cycles or $+0.014^{\mathrm{ovo}}$ at 2000 cycles.

Measuring accuracy of calipers

The ability precisely to put both legs of the calipers on the right spots differed by as much as 0.009 inch, corresponding to $+0.034^{\mathrm{ovo}}$ at 300 cycles or $+0.005^{\mathrm{ovo}}$ at 2000 cycles.

Reading accuracy of calipers

For the measuring instrument used the least count (Whitehead: 102) is 0.001 inch, equivalent to 0.0028^{ovo} at 300 cycles or 0.00042^{ovo} at 2000 cycles. That is to say, with both legs of the caliper on the right spots, the dial would indicate values correct to within ±0.001 inch with no detectable erratic error. The method of using the calipers was to make the adjustment in the negative direction. Any backlash, which was in fact not detectable, would have systematically placed all measurements on the positive side.

A human error in reading the caliper dial[1] of one to two thousandths would be conceivable but unlikely. A much greater error in reading the calipers would not distort the results beyond the tolerance imposed by other elements in the whole measurement process. The dial calipers are in fact the strongest link in the measurement chain.

The dial calipers used were callibrated against high grade machinists micrometer calipers of ±0.0001 inch accuracy and were found to be reliable within the specified limits indicated above. A systematic error of slightly more than -0.019 inch was discovered, for which error compensation was effected in the computation program by systematically adding 0.019 inch to all formant measurements.

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[1] The dial covers 200 divisions, with a 1/2 inch long pointer. There are thus in effect $\pi/200 = 0.0157$ linear inches between divisions.

Copying accuracy

In copying data onto the data worksheets a human error, for example transposition of adjacent digits, occurred from time to time. Gross errors caused, in a few cases, failure of the computer to compute the desired results (or any results, indeed). In other cases gross errors in copying data caused obviously absurd results to be computed. Such errors were readily detected on reexamination of the spectrograms and comparison with the data sheets. The type of graphical display chosen for computer printout was particularly sensitive to errors of the magnitude of 0.01 inch of measurement.

Punching accuracy

Errors in punching the tabulating cards occurred despite reasonable caution. They were found and corrected as above. All data were recorded, punched, and processed by the computer to 0.001 inch. Copying and punching errors of small magnitutde (i.e. errors in the third decimal place) were on occasion detected fortuitously. It must remain as unknown as it is unimportant what human errors of small magnitude are in the results. Punching errors might have been detected by verification punching, in effect a repetition of the entire punching process and comparison with the original punching. It was judged unlikely that important errors would be found in this way that could not have been more readily found by direct inspection of the printout. There would have been no means whereby unimportant errors in measuring or recording data could have been detected except to have repeated the whole process of measuring and punching, a course likewise rejected.

Computation errors

The ability of the digital computer to produce the desired results can of course theoretically be questioned. Computer errors are of two kinds: inaccuracy due to storage limitation, and programming errors. The former can be eliminated summarily as not being a factor in the present dissertation, involving as it did a relatively simple (in computer users' terms at least), small problem. Storage requirements were thus relatively modest. Programming errors, on the other hand, could have been a serious source of error, had the results not been checked very carefully by desk calculator. Several mistakes were uncovered which necessitated repeated resubmission of the entire problem. In the end the program gave satisfactory results in computing values called for by the formulas listed in this dissertation. It should be noted that programming errors are typically large errors, not at all like the small errors discussed in the above paragraphs.

Perceptual acuity

All potential sources of error must be related to the ability of a speaker or listener to produce or to detect differences in formant frequency. It would be unnecessary to waste time in the elimination of experimental errors that would be in all likelihood undetectable anyway. The purpose of this section has been to find the factors that limit the overall reliability of the results reported here, to evaluate those factors, and to find which link in the chain of measurement elements is the weakest. Regardless of whether or not the perceptual link is the weakest link in the chain (it is not in fact), it requires special attention, not only because it is the only one of direct linguistic significance, but also because it is the only link incapable of being strengthened. More efficient measurement devices can be built and more sophisticated procedures can be developed for using them, but the experimenter has no control over the ability of the listener to distinguish speech sounds.

The sensitivities of the various mechanical elements pertinent to this discussion are summarized here below:

	300 cycles	2000 cycles
Spectrograph lathe backlash (compensated)	$+0.13^{ovo}$	$+0.021^{ovo}$
Tracing	$+0.093^{ovo}$	$+0.014^{ovo}$
Caliper adjustment	$+0.034^{ovo}$	$+0.005^{ovo}$
Caliper reading	$+0.0028^{ovo}$	$+0.0004^{ovo}$

The operator's ability to trace accurately the contour of a formant is thus seen to be the most serious source of uncompensated error, as much as 0.093^{ovo}. A measuring procedure yielding results to one thousandth of an octave is therefore in order (mantissas to three places), with the hundredth place equivalent to the place of least count, and the thousandth octave the one doubtful place. Mantissas to four places are unnecessary.

The question can now be raised as to whether the human organism is able to distinguish formant frequencies with that order of acuity. The tentative answer must be affirmative (Flanagan, 1955: 617). Flanagan estimated a difference limen for detecting quality difference, here converted to octaves, ranging from 0.0143^{ovo} at 2000 cycles for the second formant to 0.0841^{ovo} at 300 cycles for the first formant of synthetic vowels. Rule-of-thumb figures of 3% to 5% (0.043^{ovo} to 0.074^{ovo}) are suggested by Flanagan (1955: 616). Three place mantissas then do not introduce illusory sensitivity.

On the basis of this survey of formant frequency determination errors, the decision was made to retain enough significant figures in the final results to provide for the thousandth part of the octave (i.e. three place mantissas) but no more. Of this three place mantissa, the first place is surely not doubtful, the second place is probably not doubtful, and the third place (thousandths place) is surely doubtful.

Chapter 5. Results

This chapter contains a list of the acoustic phonetic results from the computations based on sound spectrograms of the front vowels in monosyllabic words. Several hundred pages of computer printout are summarized in this chapter. The generalizations herein are supplemented by tables and graphs of results. Acoustic measures of the first two formant frequencies are discussed. Data approximating vowel duration in seconds are also supplied.

The following phonetic parameters are derived from the physical measures: height (cf. tongue height), frontness, aperture, and diffuseness.[1] The acoustic phonetic parameters are discussed in an attempt to answer two phonological questions: 1. how do the phonetic parameters vary with differing vowels; and 2. how do the parameters vary with differing consonants after the vowels? Expressed in another way, what cues do the listed phonetic parameters provide for the identification of vowels and consonants? Of the acoustic phonetic parameters, aperture

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[1] The relationships between the acoustic phonetic parameters and the corresponding physiological phonetic parameters are outlined on pages 26-28. For precise definitions of the acoustic phonetic parameters, see pages 35-44.

and diffuseness will receive the most attention. The generalizations offered here are intended to show patterned variations between equivalence classes of events that appear despite random variations within such classes. It was to have been expected that in isolated instances extreme variation within equivalence classes of words would exceed normal variation between classes. In other words the classes of words tended slightly to overlap. As the amount of data was too small to permit a full-scale statistical analysis, reliance was placed on three simple indices of variability: arithmetic mean, maximum, and minimum values for both aperture and diffuseness. Of these it is the mean that is most trustworthy.[2]

Typical plots of the aperture and diffuseness values for individual samples appear in Figures 5 through 10.

Table 1

The list of different words in the corpus is shown in Table 1 following in the order in which the samples were processed by the computer. As it had been

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[2] It should be explained that time, expense, and the availability of equipment place limits on the number of sound spectrograms that can or should be made in investigating a problem in phonetics. While the data supplied in this dissertation would appear to be sufficient to discover the central tendencies of phonetic patterns in question, they are not enough to establish standard deviations. One would hope that reliable and efficient automatic formant tracking devices could be perfected during the next few years.

anticipated that within any one of the 41 consonantal contexts the variation would be in traditional order, the words were punched onto tabulating cards in that order. It will be noted that in general voiceless codas come before voiced and that labial and apical codas precede velar codas. Except for the last six word types, the obstruent codas precede the -*l*, -*m*, and -*n* codas.

The numerical data reported in Table 1 are the synopsis of results of the computation of aperture and diffuseness for all samples in the corpus. The number of word tokens (the number of individual samples) of a particular word type are given in the second column. The value for mean aperture and mean diffuseness are the arithmetic means of all words of a particular type (i.e. the sum of the means divided by the number of tokens of that particular word type). Maximum and minimum aperture and diffuseness are the extreme values selected from all tokens of a particular word type. For example, for the word *meat*, the minimum, 2.649^{ovo}, was the lowest value for diffuseness found at any measured instant in any of the six individual sample tokens of the words of type *meat*. It happens to lie just above the maximum diffuseness, 2.621^{ovo}, of the word *mitt*, below which value all other diffuseness values for the six tokens of *mitt* lay. The range is, of course, the minimum (aperture or diffuseness) subtracted from the maximum. Graphs showing the changes in aperture and diffuseness

TABLE 1. SYNOPSIS OF DIFFUSENESS AND APERTURE VALUES.

WORD		DIFFUSENESS				APERTURE			
TYPE	N	MEAN	MAX	MIN	RANGE	MEAN	MAX	MIN	RANGE
SHEEP	3	3.054	3.429	2.712	.716	2.267	2.526	1.944	.581
SHAPE	2	2.519	2.953	2.014	.938	2.731	3.091	2.441	.650
REAP	6	2.576	2.973	1.658	1.315	2.480	2.830	2.222	.607
RIP	6	1.778	2.001	1.535	.466	3.059	3.314	2.564	.750
RAP	5	1.237	1.838	.634	1.205	3.618	4.154	2.638	1.516
KEEP	6	3.117	3.954	2.671	1.283	2.284	2.645	1.724	.921
CAP	6	1.258	1.847	.691	1.156	3.753	4.081	3.355	.726
PIP	6	1.855	2.570	1.520	1.050	3.143	3.368	2.555	.813
PEP	2	1.447	1.821	1.167	.654	3.495	3.620	3.240	.379
LIP	6	1.787	2.226	1.476	.750	3.109	3.339	2.634	.704
LAP	6	1.115	1.761	.706	1.055	3.691	3.998	2.686	1.312
FIT	6	1.790	1.932	1.608	.324	3.189	3.389	3.006	.383
FATE	6	2.575	3.141	1.886	1.255	2.634	3.124	1.971	1.154
FAT	2	1.200	1.572	.884	.688	3.772	3.978	3.331	.647
BEAT	6	2.864	3.423	2.184	1.238	2.442	3.002	1.894	1.108
BET	6	1.468	1.947	1.030	.917	3.492	3.804	3.018	.786
MEAT	6	2.974	3.342	2.649	.693	2.366	2.639	2.017	.622
MITT	6	1.861	2.621	1.520	1.101	3.175	3.599	2.460	1.138
MATE	2	2.769	3.195	2.436	.758	2.524	2.654	2.193	.461
MAT	5	1.264	1.964	.816	1.149	3.740	4.034	2.955	1.079
SET	6	1.473	1.863	1.195	.668	3.432	3.667	3.033	.634
SAT	6	1.209	1.750	.883	.867	3.726	3.930	3.108	.822
HIT	6	2.005	2.489	1.673	.816	3.090	3.319	2.765	.554
HATE	6	2.726	3.035	2.200	.835	2.558	3.050	2.232	.817
TICK	6	2.081	2.555	1.804	.751	3.029	3.247	2.653	.593
TAKE	6	2.407	3.017	1.917	1.099	2.862	3.254	2.393	.862
TACK	6	1.269	1.506	1.145	.361	3.782	3.911	3.600	.312
SAKE	6	2.265	3.183	1.546	1.636	2.903	3.308	2.245	1.063
SACK	6	1.231	1.577	.956	.621	3.749	3.949	3.267	.681
PEEK	5	2.993	3.367	2.732	.635	2.355	2.555	2.092	.463
PACK	6	1.137	1.406	.628	.777	3.861	4.050	3.721	.329
LEAK	6	2.835	3.652	2.320	1.332	2.445	2.816	1.792	1.024
LAKE	6	2.220	3.106	.701	2.405	2.914	3.797	2.299	1.498
LACK	2	1.075	1.296	.787	.509	3.786	3.926	3.152	.775
CHEEK	2	2.142	2.704	1.496	1.208	3.052	3.510	2.651	.859
CHECK	5	1.739	2.293	1.330	.963	3.286	3.622	2.904	.718
SCHICK	2	2.104	2.394	1.831	.563	2.996	3.247	2.756	.491
SHAKE	6	2.418	3.092	1.732	1.360	2.803	3.232	2.318	.914
EACH	6	3.063	3.746	2.735	1.011	2.351	2.649	1.924	.725
H	6	2.722	3.220	2.184	1.036	2.588	2.996	2.145	.851
PEACH	2	3.164	3.571	2.793	.778	2.280	2.527	2.011	.517
PITCH	6	2.042	2.163	1.932	.231	3.064	3.153	2.941	.212
PATCH	6	1.228	1.689	.903	.786	3.811	3.950	3.477	.473
PIECE	6	2.934	3.203	2.624	.579	2.391	2.647	2.189	.459
PASS	4	1.186	1.560	.670	.889	3.789	3.971	3.504	.467
BED	6	1.642	2.144	1.083	1.061	3.325	3.736	2.865	.871
BAD	1	1.362	1.645	1.064	.580	3.615	3.777	3.341	.436

TABLE 1. (CONTINUED)

WORD TYPE	N	DIFFUSENESS MEAN	MAX	MIN	RANGE	APERTURE MEAN	MAX	MIN	RANGE
DEED	6	2.984	3.466	2.730	.736	2.459	2.644	2.236	.408
DID	2	1.967	2.176	1.756	.420	3.066	3.149	2.975	.174
SEED	6	2.844	3.135	2.478	.657	2.485	2.733	2.242	.491
SAID	2	1.530	1.734	1.354	.379	3.401	3.557	3.200	.357
SAD	6	1.353	1.715	.947	.768	3.602	3.825	3.203	.622
LEAD	6	2.843	3.238	1.962	1.276	2.474	2.991	2.149	.842
LAID	6	2.337	3.261	1.118	2.143	2.820	3.532	2.166	1.366
LED	6	1.503	1.952	1.248	.704	3.372	3.554	2.875	.679
LAD	6	1.180	1.508	.537	.972	3.692	3.836	2.930	.906
FADE	6	2.523	3.087	1.894	1.193	2.721	3.159	2.263	.895
FED	6	1.691	2.042	1.320	.722	3.280	3.603	3.042	.561
FILL	6	1.189	1.916	.723	1.194	3.387	3.706	3.052	.655
FELL	6	.996	1.950	.415	1.535	3.594	3.884	3.004	.880
HEAL	3	1.788	2.976	.349	2.627	3.011	3.626	2.322	1.304
HELL	2	1.021	2.166	.606	1.560	3.565	3.763	2.928	.834
HAL	6	.825	1.435	.297	1.138	3.870	4.064	3.674	.390
BEAL	6	1.693	3.143	.690	2.454	3.064	3.593	2.127	1.466
BELL	6	1.116	2.069	.541	1.528	3.507	3.828	2.897	.931
SEAL	2	1.742	3.061	.596	2.465	3.034	3.600	2.285	1.314
SALE	6	1.601	2.351	.600	1.751	3.221	3.806	2.850	.956
TILL	6	1.199	2.287	.603	1.684	3.360	3.622	2.845	.777
TELL	6	.982	2.065	.437	1.629	3.576	3.813	2.970	.843
SEEM	3	3.078	3.544	2.817	.727	2.348	2.531	2.155	.376
SIM	6	2.441	2.781	2.011	.771	2.582	2.796	2.335	.460
SAME	6	2.711	3.990	1.639	2.350	2.541	3.215	1.139	2.076
JIM	6	2.414	3.073	.820	2.253	2.649	3.922	2.129	1.793
GEM	6	1.563	2.748	.820	1.928	3.439	3.883	2.380	1.503
TIN	6	2.569	2.717	2.361	.356	2.535	2.733	2.420	.313
TAN	2	1.334	1.560	.819	.741	3.756	3.952	3.654	.299
KIN	5	2.566	2.899	2.069	.830	2.537	2.750	2.337	.412
KEN	6	2.600	2.967	1.993	.974	2.504	2.819	2.241	.578
DIN	6	2.331	2.792	1.281	1.511	2.751	3.717	2.394	1.323
DAN	6	1.453	2.066	.852	1.214	3.627	3.969	3.020	.950
BEAN	2	3.091	3.567	2.804	.763	2.269	2.533	1.804	.729
BAN	6	1.469	1.990	.811	1.180	3.594	3.963	3.032	.930
JEANNE	6	2.984	4.453	2.438	2.015	2.394	2.859	1.093	1.765
JANE	2	2.892	3.185	2.538	.647	2.384	2.566	2.185	.381
PIN	6	2.519	2.916	1.718	1.198	2.586	3.188	2.323	.865
PAN	6	1.422	1.750	.861	.889	3.682	3.944	3.455	.489
MIN	2	2.583	2.697	2.238	.459	2.517	2.658	2.441	.217
MAIN	6	2.840	3.153	2.272	.882	2.456	2.709	2.254	.455
MEN	6	1.222	1.388	.876	.512	3.776	3.964	3.650	.314
BABE	6	2.503	2.923	1.962	.961	2.734	3.116	2.377	.739
BAB	7	1.367	1.805	.884	.921	3.604	3.901	3.198	.703
CHAFE	2	2.531	2.976	2.042	.933	2.704	3.091	2.364	.727
CHAFF	6	1.286	2.046	.751	1.296	3.711	4.039	3.107	.932
SAVE	6	2.295	2.914	1.486	1.429	2.862	3.348	2.346	1.002
SALVE	2	1.288	1.610	.953	.657	3.668	3.835	3.369	.166

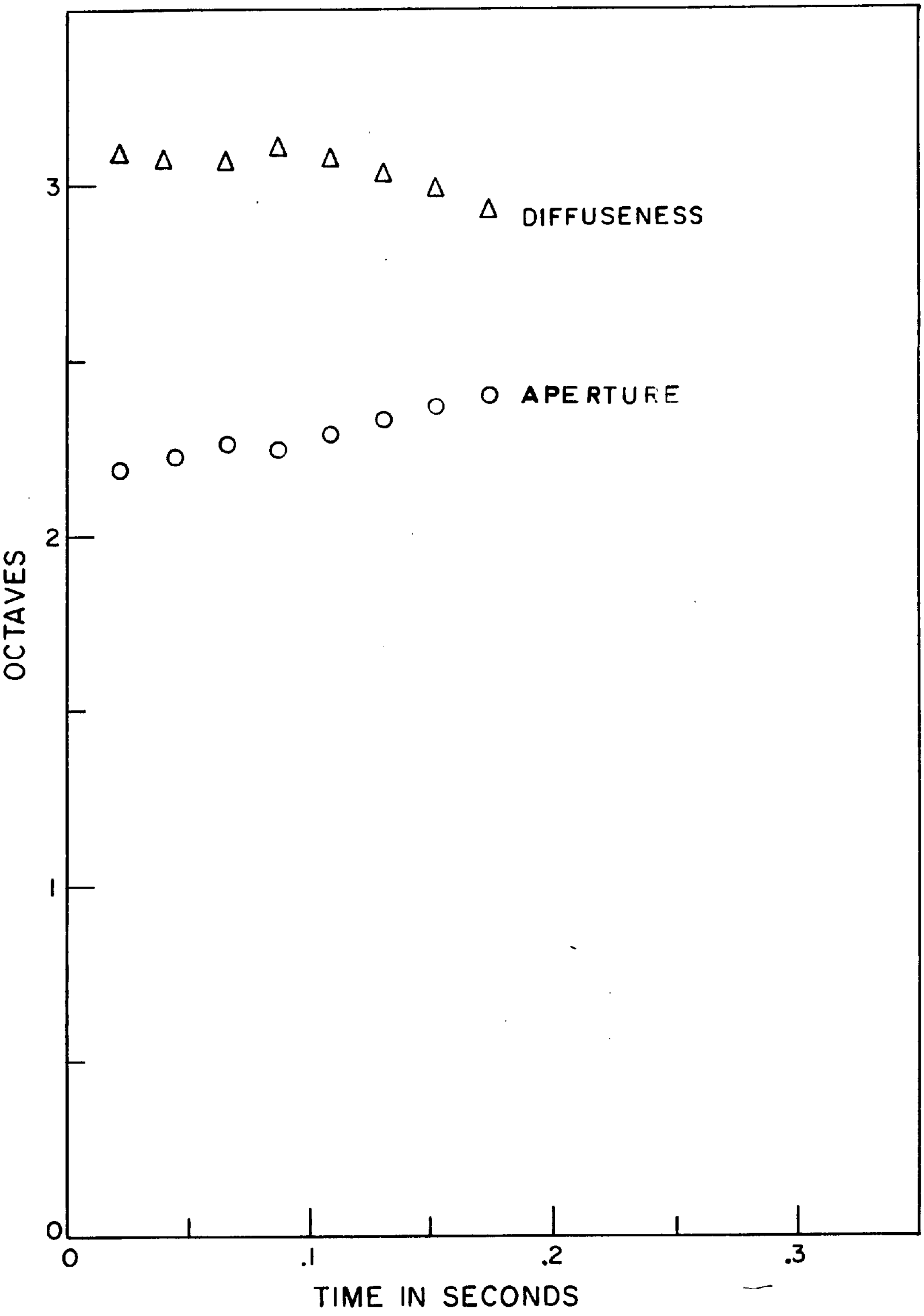

Figure 5. Plot of Diffuseness and Aperture in Sample Number 458, 'meat.'

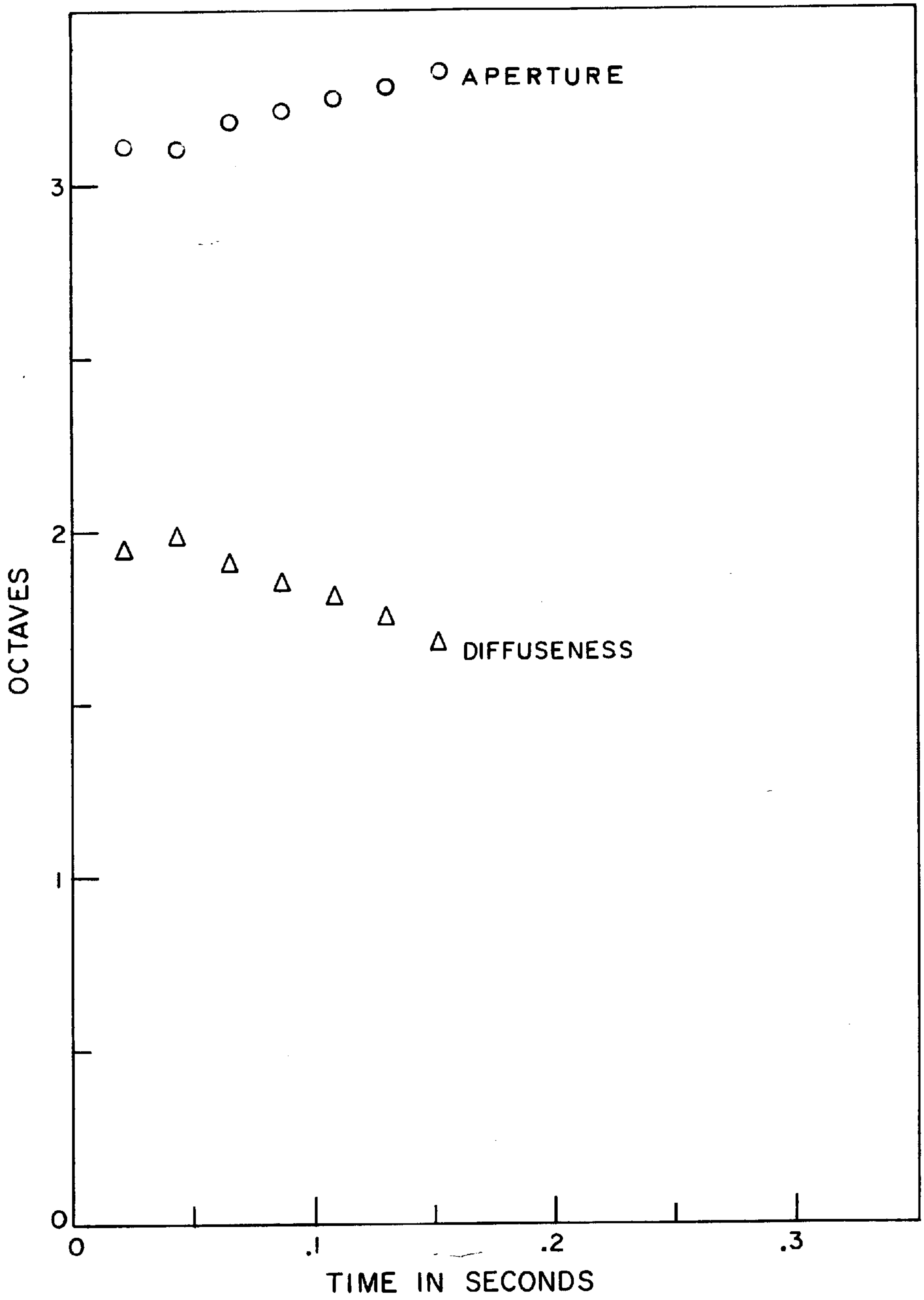

Figure 6. Plot of Diffuseness and Aperture in Sample Number 11, 'mitt.'

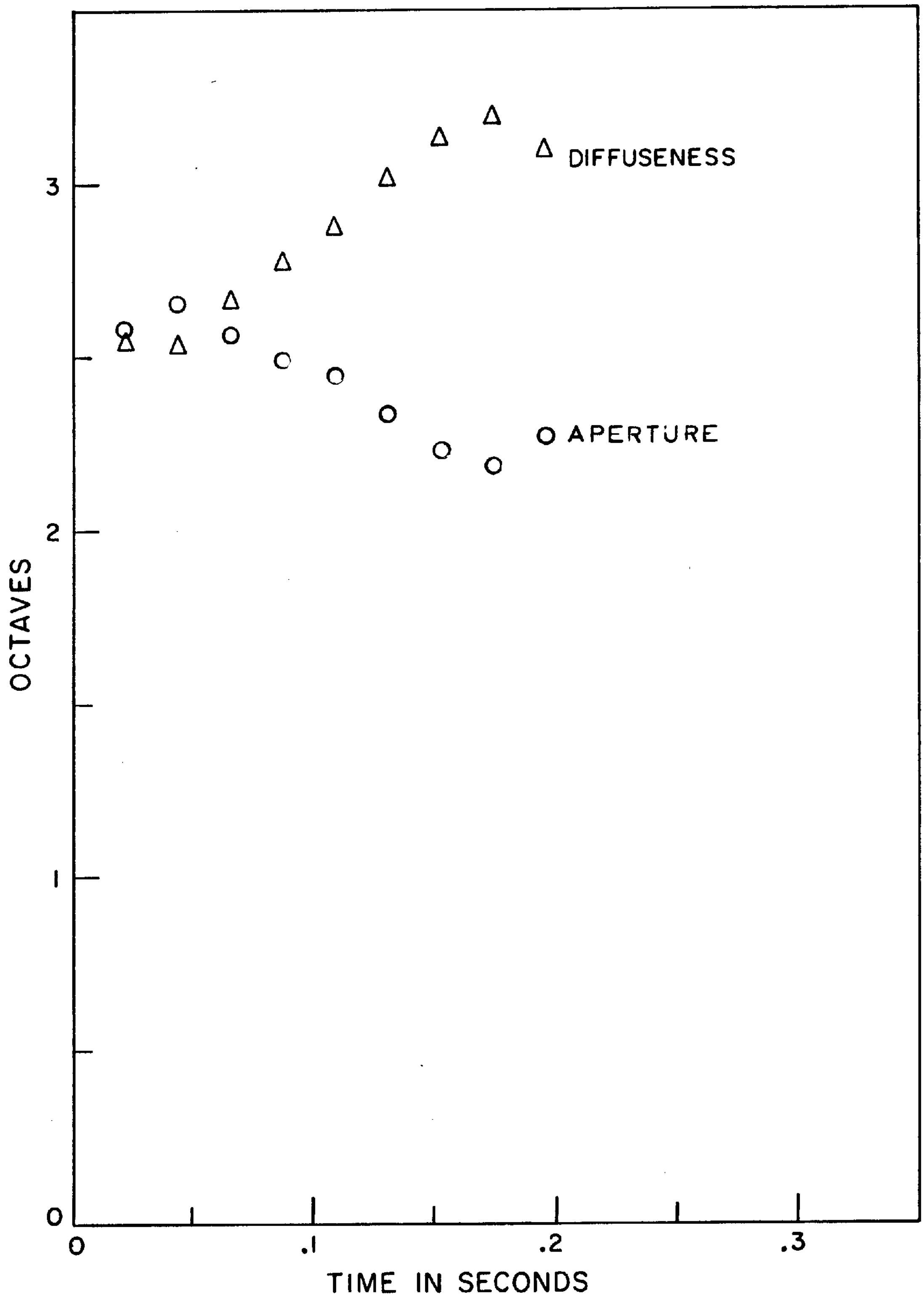

Figure 7. Plot of Diffuseness and Aperture in Sample Number 486, 'mate.'

for the words meat, mitt, and mate follow Table 1., in Figures 5, 6, and 7, pages 61-63. Other graphs and the tables of values from which the graphs were plotted appear in Appendices C and D.

In the following section the data are ranked in six continua, according to their relative static position with respect to mean, maximum, and minimum values for both aperture and diffuseness.

Differences between the vowels

In works on the phonetics of English, the front vowels are often arranged in a paradigmatic series ranging from high to low, or from front to back (Gleason, 1961: 317-328). The vowels in the following typical words are arranged in the traditional high-to-low progression: beat, bit, bait, bet, bat.[3] The data obtained in the present experiment did not fully support the traditional arrangement, in that the vowel of bait, in nearly every case, fell between those of beat and bit, with respect to both aperture and to diffuseness.[4] The mean aperture values

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[3] The words beat ... bat will be taken in this chapter to symbolize all words that share the same vowels with the beat ... bat words.

[4] Perhaps it need not be emphasized that the consonantal context was always held constant during the investigation of a particular vocalic oppostion.

supported the ranking from small aperture to large aperture as follows: <u>beat</u>, <u>bait</u>, <u>bit</u>, <u>bet</u>, <u>bat</u>. The exceptions were <u>kin</u> > <u>Ken</u>[5], and <u>Jeanne</u> > <u>Jane</u>.

It should be noted that in all cases of obstruent codas the relationship <u>beat</u><<u>bait</u><<u>bit</u><<u>bet</u><<u>bat</u> obtained for the mean aperture. The two exceptional sets of words had nasal consonant codas. A portion of the consonant was measured for all words terminating in -<u>l</u>, -<u>m</u>, and -<u>n</u>. A possible explanation for the relatively low aperture value for <u>Jane</u> might be that random variation in aperture associated with the final consonant obscured patterned variation of the vowel. Another explanation, that the final -<u>n</u> has a strong tendency to lower the preceding vocalic aperture, will be discussed below in the section on consonants.

Maximum aperture values, although less revealing of vowel patterns, show nevertheless the same relationship expressed above, with four exceptions: tick<take; Sim<same; gem<Jim; and Jane < Jeanne.

Minimum aperture values in the large majority of instances supported the relationship beat<bait<bit<bet<bat. There were the exceptions said = sad, fill > fell, seem>same, and kin>Ken.

Mean diffuseness was according to the rule

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[5] The symbolization> here means that with respect to the stated value the former was greater than the latter. Conversely, < means <u>less than</u> in that parameter.

beat>*bait*>*bit*>*bet*>*bat*, with one exception: *Ken*>*kin*. Maximum diffuseness also fit the same pattern, exceptions being *each*<*H*, and four instances of words with -*l*, -*m*, or -*n*.

Minimum diffuseness was according to pattern, with seven exceptions, all with -*l*, -*m*, or -*n*, including one instance (*Jim* = *gem*) where both words had the same minimum diffuseness value.

The values for aperture and diffuseness, with a few exceptions, provide evidence for ranking the front vowels in a continuum *beat*, *bait*, *bit*, *bet*, and *bat*. With less consistency the same vowels could be arranged in the same continuum on the basis of data for *height* (F_1) or *frontness* (F_2). The data on first formant and second formant frequency alone, although available, fully tabulated in the computer printout, are not summarized here. In general, the first formant alone gives a better cue for front vowel discrimination than does the second formant alone. Both formants taken together, as aperture or diffuseness, give better discriminability than either of the two formants alone. Sample values for first and second formants are given in Tables 2 through 7.

The values for F_1 are reported in octaves above 55 cycles per second, and for F_2 in octaves above 220 cycles per second, as is discussed on page 46. Because of this scale compression factor, 2^{ovo} must be added to all values for the first formant. A special logarithmic table is available for converting first and second formant values from octaves to cycles per second.[6]

Although differences between the five vowels with respect to duration in time were not investigated systematically, there are tabulated in the computer printout many data that deserve to be commented on briefly. Under the original hypothesis for the present experiment, it had been predicted that duration was of less importance for the discrimination of front vowels than the other parameters listed. Therefore a measure for the duration of the vowels was not recorded directly. Instead, as explained on page 31, each spectrogram was segmented into time-slices of 0.02175 second duration, equivalent to 1/8" linear distance along the horizontal time axis. The first such slice was always made just at the point near the beginning of the vocalic (nuclear) portion where the pattern for both formants could be plainly seen. The last slice was made some integral number of 1/8" intervals later, just at or just before the point where the vocalic pattern for both formants ceased, or a consonantal pattern began. The rough data for duration then do not represent time to the <u>nearest</u> 21.75 milisecond interval, but to the next <u>lower</u> interval number. But the intervals were numbered starting with one, rather than zero. The data on duration are thus overestimated.

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[6] A computer program for generating such a table can be obtained from the author on request.

Any one value for time might be just under 21.75 miliseconds too high in the extreme case. With this warning in mind, the data on vowel duration can be examined. Table 2, following, can be used to interpret the time scale.

Despite numerous exceptions, the duration relationship is clearly bat>bait>beat>bit = bet, for both voiced and voiceless codas. When vowels before voiced codas are compared with the same vowels before voiceless codas, it is usually the latter that are shorter, for example sad>sat, said>set.

One important way in which vowels differ from each other is in the extent of increase or decrease in aperture and diffuseness. As will be discussed in greater deatail below, the vowel of bait tends to show a decrease in aperture and an increase in diffuseness from the beginning to the end. The vowel of bat conversely, increases in aperture and diffuseness will be discussed below in the section on differences within the vowels. In the foregoing paragraphs the influence of the final consonant has not been pointed out. The noted differences between the vowels occur regardless of what consonant follows.

Differences within the vowels

As was to have been expected (Lehiste and Peterson, 1961: 268-227), the movements of the first two formants during the vowel were quite apparent. Particular attention

Table 2. Table for Reading Time Scale from Spectrograms.

T = time in eighths of an inch of spectrogram length	Time in centiseconds.
1	2.175
2	4.350
3	6.525
4	8.700
5	10.875
6	13.050
7	15.225
8	17.400
9	19.575
10	21.750
11	23.925
12	26.100
13	28.275
14	30.450
15	32.625
16	34.800
17	36.975
18	39.150

has been devoted in the present experiment to the changes in formant frequencies at the ends of the vocalic nuclei. It had been hoped that the data would reveal dynamic changes, in particular in aperture and diffuseness, that could be clearly associated with (1) the consonants alone, and with (2) the vowels alone. The data were unfortunately insufficient to show such differences in dynamic aperture and diffuseness with statistical confidence. It had been anticipated that there could be found clearly bounded target positions for diffuseness and aperture, similar to the formant target positions found by Lehiste and Peterson (1961). Instead of assuming clear target positions, the diffuseness and aperture values tended to change as rapidly as 1^{ovo} in 15 centiseconds, or as slowly as one octave per second, or perhaps not at all. Despite the fact that there did not emerge clearly identifiable patterns, changes could nevertheless be noted in the dynamic aperture and dynamic diffuseness values that could nevertheless be noted in the dynamic aperture and dynamic <u>nuclei</u> found by Lehiste and Peterson for dynamic formant configurations. The vowel of <u>bait</u> was found to have a decrease in aperture at the rate of about 1^{ovo} per 12 centiseconds, accompanied by an increasing diffuseness as great as 1^{ovo} in 10 centiseconds. The changes in the vowel of <u>bait</u> tended to be distributed over a considerable portion of the vowel.

Dynamic changes were also noted in the vowel of bat, as mentioned above. The peak rates of change were less extreme than the changes for bait, but as they tended to cover the entire length of the vowel, and as the vowel of bat is the longest vowel of the five, the maximum extent of change in aperture and diffuseness for bat tended to be quite large.

Vowel to consonant transition

In addition to the changes within the vowel that can be considered intrinsic to the vowel, there are in the data patterns that might be considered to be characteristic of the following consonant. In words terminating with a velar stop there was a rather clear tendency for the diffuseness to decrease toward the end of the word. Aperture in such words was either steady or slightly down. In words ending in an apical stop the diffuseness decreased on the end, except in the word hate, and aperture was either steady or slightly up. The pattern for labial stops is less clear, but it appears that the aperture curve is concave downward. Diffuseness in words with final labial stops tends to go down, except in words like shape. Additional data would be needed to investigate more thoroughly the patterns in words terminating in labial stops.

Vowel to consonant transition patterns for the other obstruents could not be specifically established as being different from the stop transition patterns. A striking characteristic of the pattern for words ending in -l is the rapid decrease in diffuseness to a very low value, sometimes below 0.5^{ovo}. In words ending in -m or -n there is a likewise a decrease in diffuseness in most cases. In some instances of the word same however there is a tendency for the diffuseness to remain steady at the end. It will be remembered that the diffuseness usually increases in words with that vowel. The net effect of the two tendencies, increasing diffuseness for the vowel and decreasing diffuseness for the nasal consonant, appears to be a cancellation.

Summary

Observation of certain acoustic phonetic parameters, in particular aperture and diffuseness, revealed on a low level of phonological abstraction that the front vowels of Midwestern American English can be arranged in continua as follows.

diffuseness: beat>bait>bit>bet>bat
aperture: beat<bait<bit<bet<bat

duration: bat>bait>beat>bit>bet

The vowel of bait was seen to have decreasing aperture and an increasing diffuseness which, because of the great extent of dynamic aperture and diffuseness change, set it apart from all other front vowels. Less extreme were the rates of change in the diffuseness and aperture in the vowel of bat. The vowels of beat, bit, and bet were found to be homogeneous in their vocalic portion. In other words, no changes in the nuclei of those words could be found that could not be attributed to the consonantal transition. These findings agree with those of Lehiste and Peterson (1961: 276-277).

An attempt was made, not completely successful, to isolate and quantify the vowel-to-consonant transitions of front vowels in terms of dynamic aperture and diffuseness characteristics. More data would be required for a definitive study of vowel-to-consonant transitions in terms of the parameters discussed here. The cost of collecting and processing sufficient date for such a study might well be prohibitive, in the present state of the art of formant measurement. The data presented here for the vowels and semiconsonants themselves may, however, be of some value in phonological research.

Phonemic interpretation

As was stated in chapter 1, the present dissertation is not intended as a work of phonemics but as a contribution to phonetics. A phonemicist is invited to draw whatever conclusions he wishes from the data presented here. Nevertheless, the phonetic data presented here have been collected with a view toward their possible application in the phonemics of American English. It might be desirable at this point to return to the first chapter. Under Assumption 2 (page 4), the search has been for those acoustic phonetic patterns of speech events that are the most predictable (least random). It is held here that answers, tentative though they may be, have been suggested for Questions 1 and 2 for the present corpus. The answer to Question 1 (page 7) is that the front vowels are similar to each other and dissimilar to each other according to the continua listed in the summary. Similarity is thus seen to be, on the second level of phonological abstraction, not as an absolute opposition but as a relative continuum. Under Assumption 6 (pages 5 and 6), the parameters of acoustic phonetics do not always agree with each other. A phonologist is thus free to choose one parameter in preference to another, provided he does so on sound theoretical grounds.

Appendix A

Derivation of Aperture Formula

In this section an attempt will be made to show how the definition of aperture (p. 43) was derived.

In accordance with previous data reported in the literature, (Joos, 1948: 52; Hockett, 1955, 195), it was to have been expected that the present front vowel data, when plotted in F_2F_1 space would lie within an elipse whose longer axis would have a negative slope (i.e. would slope downward from left to right in the first quadrant). The aperture line is taken to be that long axis, a straight line. The general form for a linear equation corresponding to such a line is $A = \alpha y - \beta x + k$. It will be noted that the coefficient of y is positive and the coefficient of x is negative. If, as was expected, the slope of the line were steep, the absolute value of α would be greater than the absolute value of β. In fact, arranging the data of Peterson and Barney (1952) in the manner outlined here would yield a line approximately 17° off the vertical. Other data for other speakers could be expected to give different aperture lines, but their slopes would certainly be negative and probably steep.

The following drawing, Figure 11, will be referred to in explaining the formula for aperture. It is desired to consider the aperture value of a point, p, on

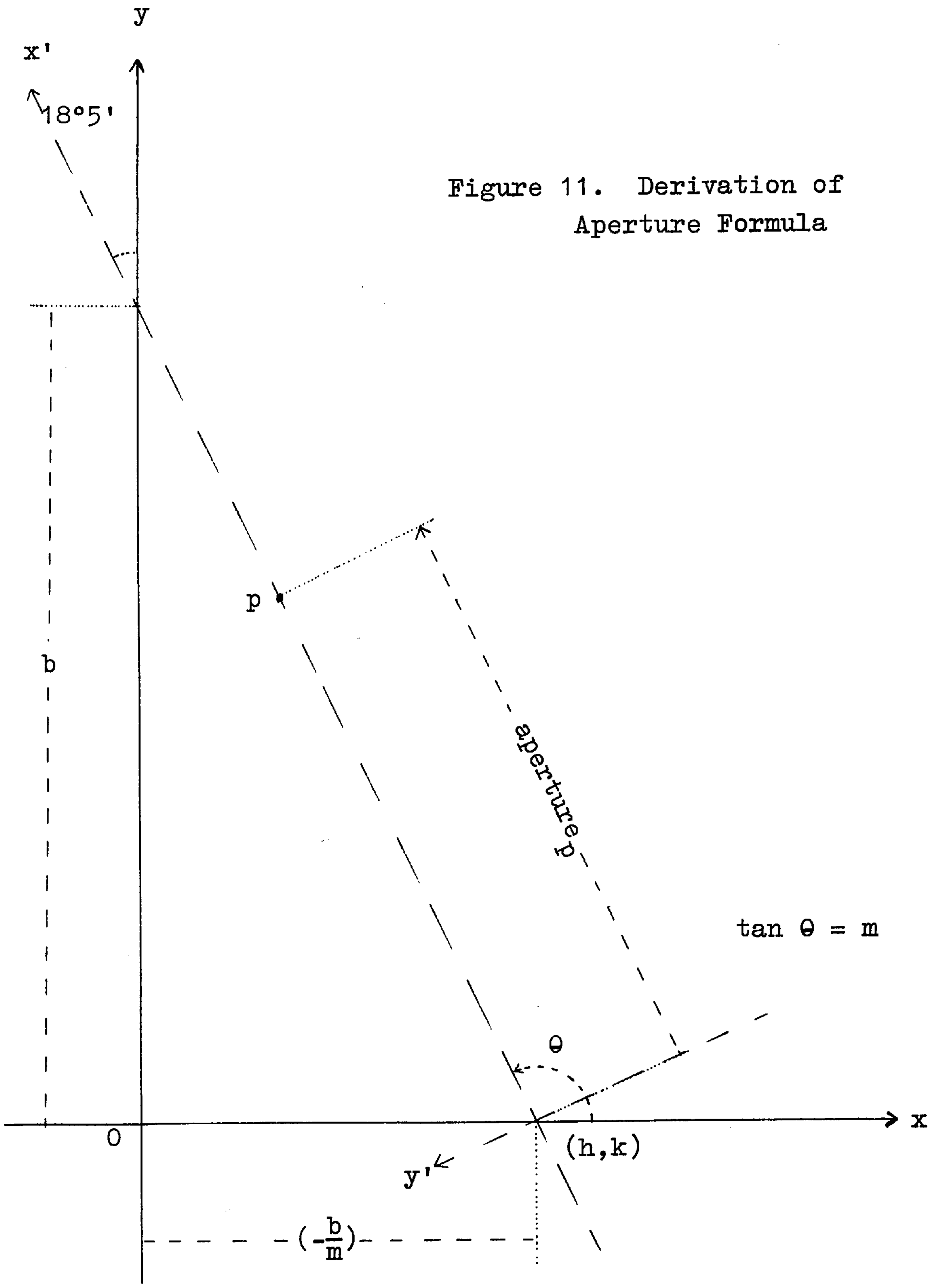

Figure 11. Derivation of Aperture Formula

the aperture line. The aperture line is designated here as one of a pair of new rectilinear coordinates, namely the axis of abscissas (x'). The origin is the point of zero aperture, the arbitrary reference point mentioned on page 38. The standard formulas for expressing the relationship between the old set of coordinates (x,y), and the axes (x', y'), are

$$x' = (x - h)\cos \theta + (y - k)\sin \theta$$

and

$$y' = (y - k)\cos \theta + (x - h)\sin \theta,$$

where θ is the angle through which the old x axis is rotated counterclockwise, and (h,k) is the point (in the old system) to which the origin is moved. The value of h has been chosen to be $-\frac{b}{m}$, and k =0. The angle θ has m as its tangent.

$$\cos \theta = \frac{1}{\pm\sqrt{\tan^2\theta + 1}} = \frac{-1}{\sqrt{m^2 + 1}} .$$

$$\sin \theta = \tan\theta.\cos \theta = \frac{\tan \theta}{\sqrt{\tan^2\theta + 1}} = \frac{-m}{\sqrt{m^2 + 1}} .$$

$$x' = \frac{-x - \frac{b}{m} - ym}{\sqrt{m^2 + 1}} = \text{aperture},$$

Evaluating the formula by replacing the slope and intercept data which were empirically derived yields

$$\text{aperture} = 1.2350 - .3104x + .9506\,y,$$

satisfying the conditions that x be negative, that y be positive and that $|y| > |x|$. The value of θ, which does not enter into the computation program, is equal to 108° 5', an angle 18° 5' off the vertical.

Appendix B. MAD Computation Program

```
          R PROGRAM FOR FRONT VOWEL APERTURE      J. A. REEDS
           I'RDD
           I'R PODA, CCNT,DAR
           D'N CRUD(6*10)
           R'T $I2*$, ZIPZIP
           CCNT=0
           R'T $C6*$, PODA
           INTEGER ZIPZIP
          R PRELIMINARIES AND GENERAL INPUT
           V'S OUT 1= $39H DETERMINATION OF FRONT VOWEL APERTURES,/13H      003
          1J. A. REEDS,/2C6*$                                                 3
           V'S Z(0)=834.,583.,875.                                            4
           T'H S9, FOR T=1,1,T.G.18
S9         TIME(T)=T                                                          6
           R'T $12I4*$, SN(1,1)...SN(41,24)
           R'T $40I2*$, MAX(1)...MAX(41)
           R'T $12C6*$, CN(1)...CN(41)
           R'T $24I2*$, TOP(1,1)...TOP(41,24)
           INTEGER TOP, MAX, CN, NAME, COW, SN, TIME, T, N, R, S, LLA,      017
          1LLB, ALPHA,  BETA, ZZ, ATHENE, ZEUS                              017
           D'N F1(24*18),F2(24*18), NAME(24), TOP(41*24), MAX(41),COW
          1(816),CN(41),SN(41*24),TIME(18),P(24),Q(24), S(24), AQ(24*
          218), DQ(24*18),MOSES(816), DATA(24*2)
           W=1./ELOG.(2.0)                                                  021
          R ITERATION WHICH CONSIDERS EACH CONTEXT ONE AFTER ANOTHER
           T'H S1, FOR R=1,1,R.G.41
          R IMPUT OF FORMANT FREQUENCY DATA FOR PARTICULAR CONTEXT
           R'T $12C6*$, NAME (1)...NAME(24)
           R'TGEORGE, LLA, LLB                                              023
           V'SGEORGE=$2I2*$                                                 024
           R'T HENRY,S(1)...S(MAX(R))                                       025
           T'HS76,FORN=1,1,N.G.MAX(R)                                       026
           R'TIN5,F1(N,1)...F1(N,TOP(R,N))                                  027
S76        R'TIN5,F2(N,1)...F2(N,TOP(R,N))                                  028
           W'R R.L.ZIPZIP,T'OS1
           V'S HENRY=$72I1*$                                                029
           V'SIN5=$15F4.3*$                                                 030
S23        CONTINUE                                                         038
          R
          R ITERATION WHICH CONSIDERS EACH VOWEL SAMPLE ONE AT A TIME
          R
           T'HS4,FORN=1,1,N.G.MAX(R)                                        068
           EXECUTE PLOT1.(0,5,10,6,15)                                      069
           EXECUTE PLOT2.(COW,30.,0.,5.,0.)                                 070
           P'T OUT 6,SN(R,N), NAME (N),R
           V'SOUT6=$11H1FOR SAMPLE I4,16H, APPEARING IN ' C6,1H', OF CO
          1NTEXT NUMBER I3,1H0*$
           P'T OUT 7
           V'SOUT7=$1H0S11,H+T+,S10,        H+D+,S9,H+APERT+,S11,H+X+,S
          112,H+Y+,1H0*$
           MED=0                                                             86
           MEA=0                                                             92
           WWD=0                                                            113
           WWA=0                                                            116
           MND=200.                                                         125
           MNA=200.                                                         128
           MXD=-200.                                                        137
```

Appendix B (Continued)

```
          MXA=-200.                                                          140
         R ITERATION WHICH CONSIDERS EACH INSTANT OF TIME ONE AT A TIME
          T'HS5,FORT=1,1,T.G.TOP(R,N)                                        143
         R COMPUTATION OF FIRST AND SECOND FORMANTS IN OCTAVES, AS WELL AS
         R DIFFUSENESS AND APERTURE
          X=W    *ELOG.((F2(N,T)+.019)*Z(S(N))/220.)                         144
          Y=W    *ELOG.((F1(N,T)+.019)*Z(S(N))/55.)                          145
          D=W    *ELOG.((F2(N,T)+.019)/(F1(N,T)+.019))                       146
          APERT= 1.2350 - .3104*X + .9506*Y
          DQ(N,T)=D                                                          148
          AQ(N,T)=APERT                                                      149
         R
         R PRINT OF TABLE OF ABOVE-COMPUTED QUANTITIES
         R
          P'TOUT8,T,D,APERT,X,Y
          V'SOUT8=$S10,I2,4F13.4*$
          INT=TIME(T)                                                        172
          EXECUTE PLOT 3.($D$,INT,D,1)                                       175
          EXECUTE PLOT 3.($A$,INT,APERT,1)                                   176
          MED=D+MED                                                          179
          MEA=APERT+MEA                                                      180
S7        CONTINUE                                                           191
          WWD=WWD+D                                                          206
          WWA=WWA+APERT                                                      207
          W'RMNX.G.X,MNX=X                                                   216
          W'RMND.G.D,MND=D                                                   218
          W'R MNA.G.APERT, MNA=APERT                                         219
          W'RMXD.L.D,MXD=D                                                   222
          W'RMXA.L.APERT,MXA=APERT                                           223
S5        CONTINUE                                                           242
         R
         R
         R COMPUTATION OF STATISTICAL QUANTITIES
         R
          MED=MED/TOP(R,N)                                                   265
          MEA=MEA/TOP(R,N)                                                   266
          RND=MXD-MND                                                        277
          RNA=MXA-MNA                                                        278
         R PRINT OF TABLE OF STATISTICAL QUANTITIES
          P'T OUT9,MED,MEA
          P'T OUT11,MXD,MXA
          P'T OUT12,MND,MNA
          P'T OUT13,RND,RNA
XERXES    C'E
          W'R PODA .NE. NAME(N)
          MAXD=0.
          MAXA=0.
          T'HM7,FORDD=1,1,DD.G.CCNT
          W'RMAXD.LE.CRUD(2,DD),MAXD=CRUD(2,DD)
          W'RMAXA.LE.CRUD(5,DD),MAXA=CRUD(5,DD)
M7        C'E
          MIND = MIN.(CRUD(3,1)...CRUD(3,CCNT))
          MINA = MIN.(CRUD(6,1)...CRUD(6,CCNT))
          RANGD = MAXD-MIND
          RANGA = MAXA-MINA
          MEAND = 0
          MEANA = 0
          T'H XXERR, FOR DAR = 1,1,DAR.G.CCNT
          MEAND = CRUD(1,DAR)+MEAND
```

Appendix B (Continued)

```
XXERR          MEANA = CRUD(4,DAR)+MEANA
               MEAND = MEAND/CCNT
               MEANA = MEANA/CCNT
               P'T$S9, C6,I1,8(S2,F5.3)*$,PODA,CCNT,MEAND,MAXD,MIND,RA
              1NGD,MEANA,MAXA,MINA,RANGA
               CCNT=0
               PODA =NAME(N)
               T'O XERXES
               O'E
               CCNT=CCNT+1
               CRUD(1,CCNT)=MED
               CRUD(2,CCNT)=MXD
               CRUD(3,CCNT)=MND
               CRUD(4,CCNT)=MEA
               CRUD(5,CCNT)=MXA
               CRUD(6,CCNT)=MNA
               E'L
               V'SOUT9=$1H0,S3,H+MEANS +,S2,4F13.4*$
               V'SOUT 11=$1H0,S3,H+MAXIMA+,S2,4F13.4*$
               V'SOUT 12=$1H0,S3,H+MINIMA+,S2,4F13.4*$
               V'SOUT 13=$1H0,S3,H+RANGES+,S2,4F13.4*$
              R
              R PRINT OF GRAPH OF DIFFERENCE BETWEEN FORMANTS, AND APERTURE
              R
              R
               PRINT COMMENT$1PLOT OF DIFFERENCE BETWEEN FORMANTS IN OCTAVES
              1 (D), AND APERTURE (A) IN OCTAVES ABOVE REFERENCE$
S4             EXECUTE PLOT4.(12,ORD)                                       298
               ATHENE=1                                                     299
               V'SORD=$     OCTAVES$                                        300
S102           EXECUTE PLOT1.(0,5,10,6,15)                                  301
               EXECUTE PLOT2.(MOSES,30.,0.,6.,1.)                           302
               V'S HERA=$     OCTAVES$                                      303
S101           CONTINUE                                                     304
               T'H S100,FORN=1,1,N.G.MAX(R)                                 305
               W'R N.LE.LLA
               ZEUS= $+$
               O'R N.GE.LLB
               ZEUS=$-$
               O'E
                ZEUS=$0$
               E'L
               T'H S100,FORT=1,1,T.G.TOP(R,N)                               313
               W'R ATHENE.E.1                                               314
               AJAX=AQ(N,T)                                                 315
               O'E                                                          316
               AJAX=DQ(N,T)                                                 317
               E'L                                                          318
               INT=T                                                        319
               EXECUTE PLOT 3.(ZEUS, INT,AJAX,1)                            320
S100           CONTINUE                                                     321
              R
              R
              R COMPOSITE PLOTS OF CHANGE IN APERTURE AND DIFFUSENESS
              R FOR EACH CONTEXT
              R
               W'R ATHENE.E.1                                               322
               PRINT COMMENT $1COMBINED APERTURES$                          323
               O'E                                                          324
```

Appendix B (Continued)

```
               PRINT COMMENT $1COMBINED DIFFUSENESSES$                               325
               E'L                                                                   326
               P'T HERMES, NAME(1), NAME(MAX(R))
               V'S HERMES=$S11,12(C6,S4)*$                                           328
               EXECUTE PLOT4.(11,HERA)                                               329
               W'R ATHENE.NE.1,T'OS1                                                 330
               ATHENE=ATHENE+1                                                       331
               T'O S102                                                              332
S1             CONTINUE                                                              333
               E'M                                                                   334
              R
              R THAT WAS PROGRAM FOR FRONT VOWEL APERTURE WITH STANDARD M AND B
```

APPENDIX C

TABLES OF DIFFUSENESS, APERTURE, FIRST, AND SECOND FORMANTS IN THE WORDS 'MEAT,'MITT,' 'MATE,' 'MAT,' 'DEED,' AND 'DID.'

Table 3. Diffuseness, Aperture, F_2, and F_1 in the word 'meat,' Sample Number 458.

Time Interval Number	Diffuseness in Octaves	Aperture in Octaves	X (F_2)	Y (F_1)
1	3.093	2.194	3.122	2.028
2	3.073	2.234	3.154	2.081
3	3.071	2.258	3.188	2.117
4	3.101	2.248	3.218	2.117
5	3.077	2.285	3.238	2.161
6	3.031	2.335	3.250	2.219
7	2.987	2.367	3.234	2.247
8	2.929	2.411	3.217	2.288
Mean	3.045	2.292		
Maximum	3.101	2.411		
Minimum	2.929	2.194		
Range	.172	.217		

Table 4. Diffuseness, Aperture, F_2, and F_1 in the word 'mitt,' Sample Number 11.

Time Interval Number	Diffuseness in Octaves	Aperture in Octaves	X (F_2)	Y (F_1)
1	1.953	3.120	2.875	2.922
2	1.986	3.111	2.910	2.924
3	1.906	3.176	2.893	2.987
4	1.851	3.217	2.874	3.023
5	1.811	3.245	2.859	3.048
6	1.756	3.281	2.833	3.077
7	1.676	3.334	2.798	3.121
Mean	1.849	3.212		
Maximum	1.986	3.334		
Minimum	1.676	3.111		
Range	.310	.223		

Table 5. Diffuseness, Aperture, F_2, and F_1 in the word 'mate,' Sample Number 486.

Time Interval Number	Diffuseness in Octaves	Aperture in Octaves	X (F_2)	Y (F_1)
1	2.537	2.583	2.903	2.366
2	2.525	2.645	2.981	2.457
3	2.656	2.576	3.068	2.412
4	2.768	2.514	3.139	2.370
5	2.869	2.453	3.192	2.323
6	3.012	2.339	3.228	2.214
7	3.129	2.243	3.251	2.121
8	3.195	2.193	3.270	2.076
9	3.091	2.299	3.281	2.190
Mean	2.864	2.427		
Maximum	3.194	2.645		
Minimum	2.525	2.193		
Range	.669	.452		

Table 6 . Diffuseness, Aperture, F_2, and F_1 in the word 'mat ,' Sample Number 206.

Time Interval Number	Diffuseness in Octaves	Aperture in Octaves	X (F_2)	Y (F_1)
1	1.098	3.841	2.732	3.634
2	1.215	3.772	2.798	3.582
3	1.342	3.708	2.886	3.543
4	1.449	3.659	2.969	3.520
5	1.485	3.652	3.011	3.526
6	1.484	3.667	3.033	3.549
7	1.450	3.692	3.021	3.571
8	1.384	3.720	2.968	3.584
9	1.281	3.770	2.892	3.611
10	1.170	3.813	2.795	3.625
11	1.001	3.890	2.664	3.663
12	.823	3.986	2.549	3.727
Mean	1.265	3.764		
Maximum	1.485	3.986		
Minimum	.823	3.653		
Range	.662	.334		

Table 7. Diffuseness, Aperture, F_2, and F_1 in the word 'deed,' Sample Number 309.

Time Interval Number	Diffuseness in Octaves	Aperture in Octaves	X (F_2)	Y (F_1)
1	3.180	2.350	3.495	2.314
2	3.108	2.446	3.536	2.428
3	3.130	2.460	3.591	2.461
4	3.132	2.486	3.636	2.504
5	3.155	2.484	3.666	2.511
6	3.107	2.542	3.686	2.579
7	3.098	2.557	3.695	2.597
8	3.072	2.576	3.687	2.615
9	3.041	2.586	3.656	2.615
10	3.016	2.594	3.630	2.615
11	2.992	2.601	3.607	2.615
12	2.947	2.621	3.573	2.626
13	2.877	2.644	3.502	2.626
Mean	3.065	2.535		
Maximum	3.180	2.644		
Minimum	2.877	2.350		
Range	.304	.294		

Table 8. Diffuseness, Aperture, F_2, and F_1 in the word 'did,' Sample Number 337.

Time Interval Number	Diffuseness in Octaves	Aperture in Octaves	X (F_2)	Y (F_1)
1	2.176	3.012	3.036	2.860
2	2.146	3.015	2.998	2.852
3	2.084	3.044	2.950	2.867
4	2.035	3.050	2.887	2.852
5	1.988	3.067	2.844	2.856
6	1.938	3.087	2.801	2.862
7	1.856	3.109	2.714	2.858
8	1.771	3.149	2.650	2.879
Mean	1.999	3.067		
Maximum	2.176	3.149		
Minimum	1.771	3.012		
Range	.405	.137		

APPENDIX D

PLOTS OF DIFFUSENESS AND APERTURE IN THE WORDS 'MAT,' 'DEED,' AND 'DID.'

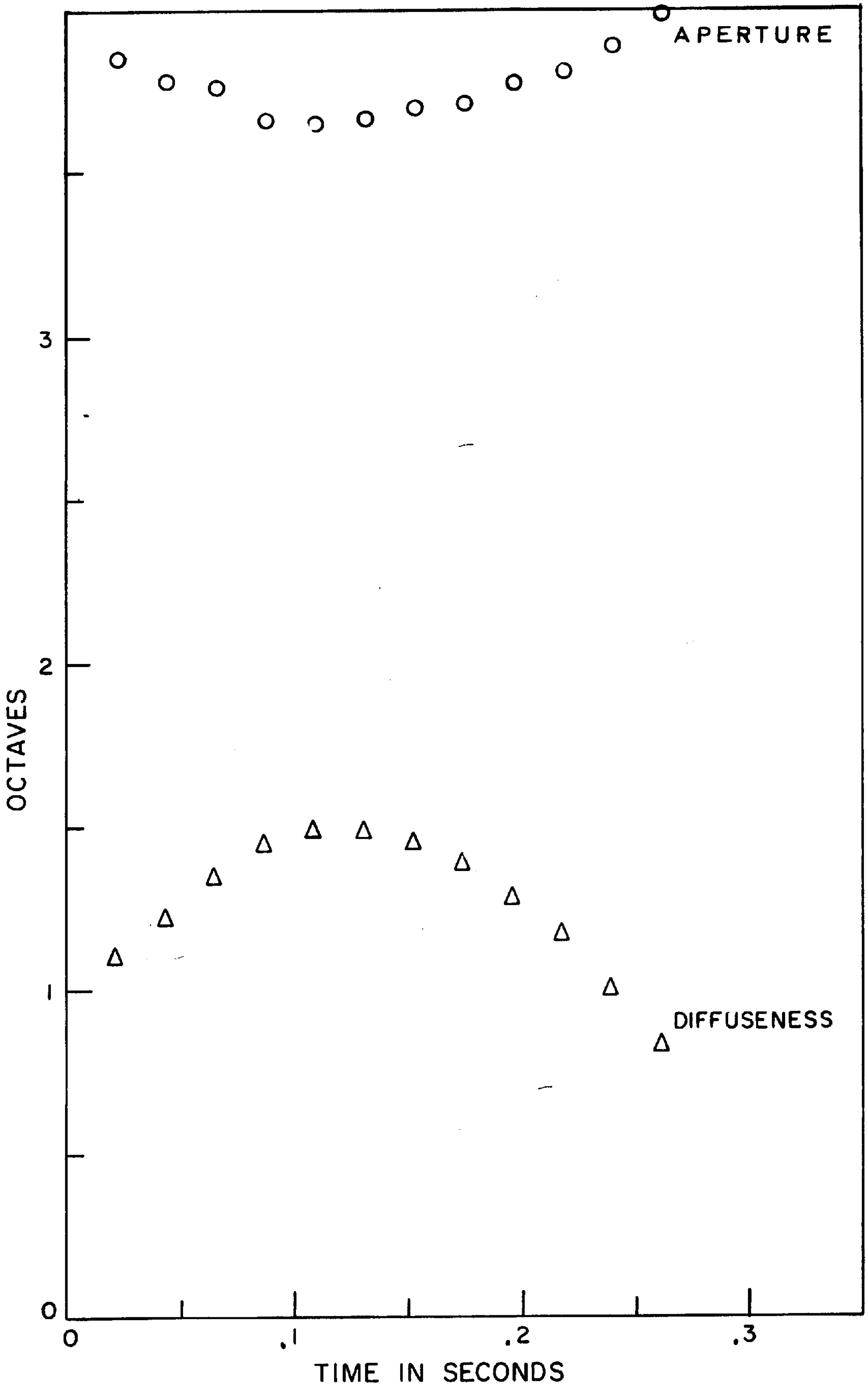

Figure 8. Plot of Diffuseness and Aperture in Sample Number 206, 'mat.'

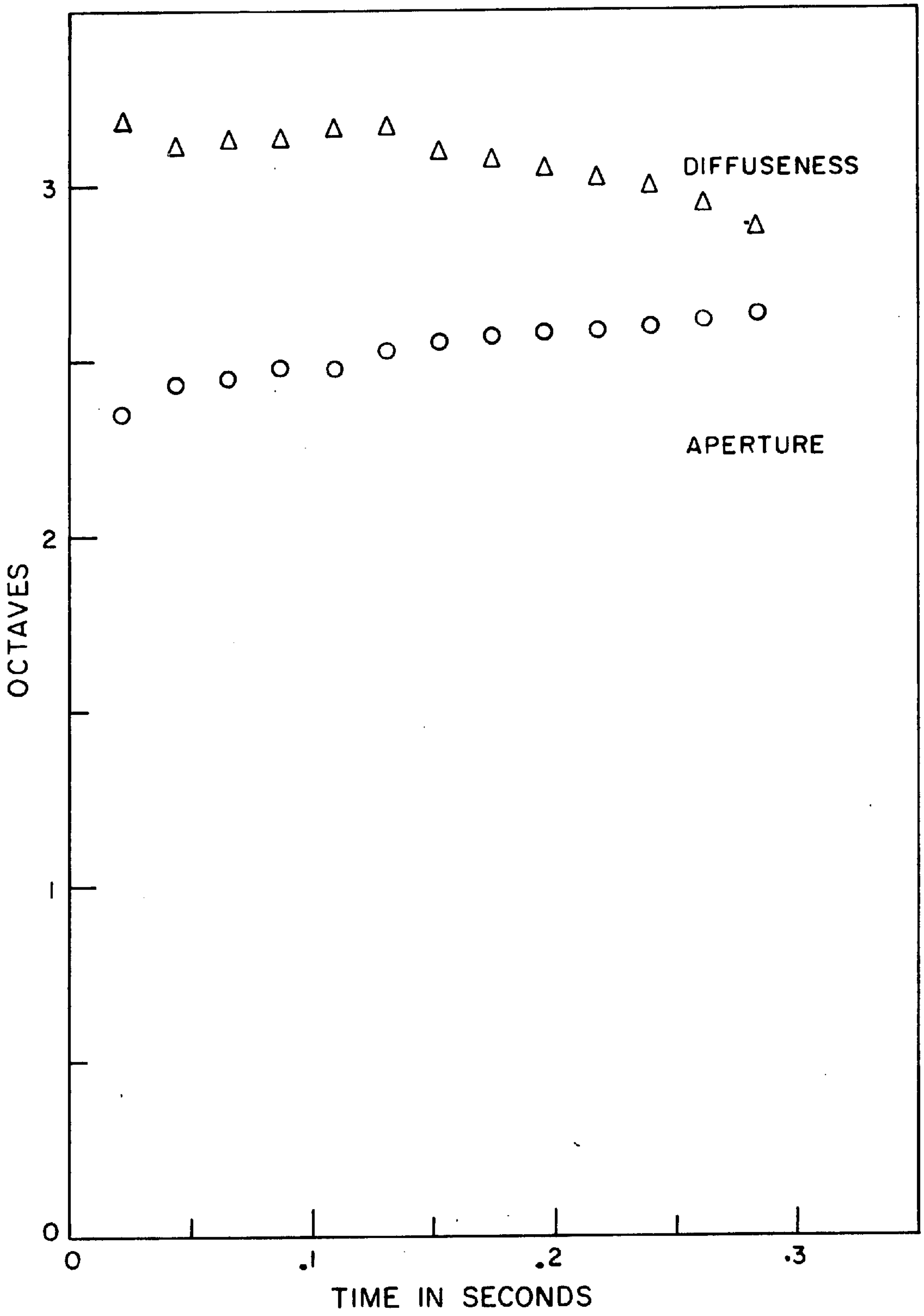

Figure 9. Plot of Diffuseness and Aperture in Sample Number 309, 'deed.'

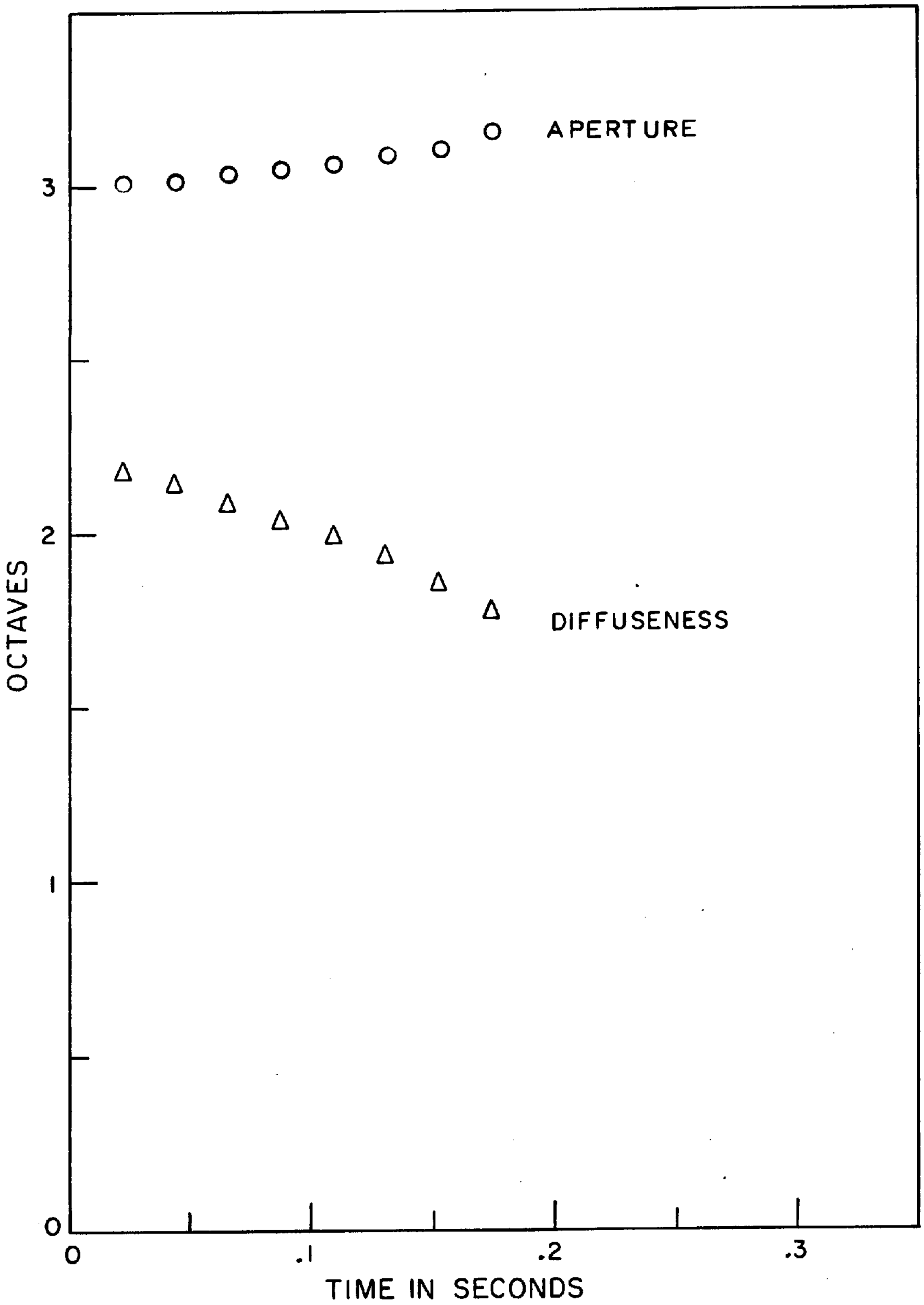

Figure 10. Plot of Diffuseness and Aperture in Sample Number 337, 'did.'

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