# VIBROTACTILE RECEPTION OF SPOKEN ENGLISH PHONEMES

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# ABSTRACT

# VIBROTACTILE RECEPTION OF SPOKEN ENGLISH PHONEMES

by

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Six subjects were presented seriatem three experimental tape recorded programs of single utterances of English Phonemes. A special tactile stimulus transmission system was designed to provide vibrotactile stimulation of the stimulus events at the finger tip. The transmission system utilized a single, cantilever mounted transducer, *viz.*, the Clevite Bimorph (PZT-5B).

The first program involved determination of intensity required for detection threshold of the phonemes. The second program was concerned with a description of the distinctive features for tactile reception of each of the phonemes. Subjects selected descriptive adjectives from a closed response set. The final program involved paired comparisons with a same-different response set to determine if additional discriminations beyond distinctive feature descriptions were possible.

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Basic data relative to vibrotactile threshold and tactile discriminations of spoken phonemes were presented primarily by descriptive methods. The data showed that thresholds of detection can be elicited for all the phonemes, with the exception of /s/ and /ɜ/. The mean threshold data and standard deviations were obtained for the remaining 36 phonemes. The vowel sounds were distributed into a compact range requiring relatively minimal energy for detection. The range for the consonants was considerably larger requiring greater stimulus intensities for detection. The tactile detection threshold responses for individual phonemes show excellent agreement among subjects and demonstrate high test-retest reliability.

The effects of the relative speech powers and inherent frequency compositions on each of the phonemes was demonstrated. Phonemes with low speech power and basically high frequency composition require more energy for detection.

Tactile distinctive features on three dimensions (intensity, duration, and pattern) were described for 33 phonemes. There was a lack of agreement among subjects, however, in judging the features of four of these phonemes.

Subjects' responses for phonemes presented by paired comparisons showed the following: (1) Phonemes differing on one or more tactile distinctive features were judged consistently as "different" by paired comparisons. (2) Identical phonemes with the same tactile distinctive features sets were discriminated consistently as "same" by paired comparisons. (3) Different phonemes with the same tactile distinctive feature sets were discriminated as "different" on 42 percent of the trials by paired comparisons. This finding suggests that the resolving power of the three dimensional tactile distinctive feature sets is not absolutely conclusive.

# VIBROTACTILE RECEPTION
# OF SPOKEN ENGLISH
# PHONEMES

By

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# TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# LIST OF APPENDICIES

# CHAPTER I

# INTRODUCTION

The notion that the cutaneous sensory receptors can aid the deaf and profoundly hard of hearing in the understanding of speech is neither novel nor new. Following Gault's early explorations of tactile discrimination in the 1920's, scientists have continued to study this sensory modality for communication purposes. The potentials continue to challenge and intrigue researchers.

Five decades ago it was assumed that the deaf could be taught to "hear through the skin." The basis for the assumption was that soumds have their own inherent characteristic vibratory patterns. As a result the observer would feel associated distinct patterns of stimulation. Thus a damaged or inoperative auditory channel could be circumvented. Both mechanical vibrations and electrical impulses were employed as sources of stimulation in these efforts.[1]

The relevant literature indicates two views as to the utility of taction in sensory communication. Early

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[1] Frank A. Geldard, "Hearing Through the Skin," Research Reviews, Office of Naval Research, Department of the Navy, Washington, D. C. (October, 1954), pp. 15-20.

investigators held that the cutaneous sensory receptors could serve as a substitute for the sophisticated, analytical capability of the human ear. This position has little support at this time. Recent research describes many similarities between audition and taction as well as some significant differences.

Of significance is the limited capability of the skin to receive the frequencies within the critical speech range. Geldard has summarized those findings:

> It is clear that, at very low frequencies, judgments of vibratory "rate" are quite good, but it is equally clear that the discriminability fades rapidly as the frequency scale is ascended. In the region best for speech sounds the skin does very badly indeed, and this finally explains why the "hearing through the skin" programs, alluded to earlier, yielded such disappointing results.[1]

The currently accepted approach is that tactile stimulation can provide a supplement for auditory or visual communication for persons with seriously impaired hearing. This idea, however, has received only limited systematic study.

The use of supplementary tactile information is a basic aspect of Guberina's approach to aural rehabilitation.

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[1] Petar Guberina, "Deaf Patients Learn to Listen on a New Wavelength," Journal of Rehabilitation, 31 (November-December, 1965), pp. 20-21.

The vibromechanical device he uses is similar to, but larger than, a conventional bone conduction receiver. His students grasp the vibrator in one of their hands to receive information to supplement auditory and visual communication. Guberina and his associates have reported considerable success employing this technique.[1] The relevant literature does not describe, however, the information transmitted and received.

Geldard and his associates have suggested that speech signals can be recoded more practically into various patterns. Specifically, Geldard advocates transposing written and verbal information into special stimuli optimally adapted to the cutaneous sensory receptors. He calls this coded language "vibratese language." A 60 Hz sinusoidal signal of varying intensities and durations provides the basis for stimulation. The signals are presented in various patterns over designated loci. Several vibromechanical stimulators are used simultaneously. Each letter of the alphabet has a specified coding or set of distinctive features.[2]

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[1] Petar Guberina, "Deaf Patients Learn to Listen on a New Wavelength," Journal of Rehabilitation, 31 (November-December, 1965), pp. 20-21.

[2] Frank A. Geldard, "Adventures in Tactile Literacy," American Psychologist, 12 (1957), pp. 115-124.

The unique applicability of this approach is in providing blind persons with the advantage of tactile sensory communication. Its utility for the hearing handicapped individual has not been demonstrated. It would appear to be a difficult system to teach to the deaf.

Research efforts in the United States and Sweden have led to the development of a reasonably efficient, but perhaps overly cumbersome, tactual vocoder. With this device, which incorporates a downward frequency transposition and separate vibrator for each finger of both hands, Pickett has found that lipreading success is significantly enhanced when stimulus materials are presented conjointly through the visual and tactual modalities.[1]

Johnson, using a completely different stimulus transmission system, (a series of loudspeakers placed on the forearm) found similar results.[2] In both studies the speech code was directly submitted to vibromechanical transduction. In other words, the speech signals were not

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[1] J. M. Pickett, "Tactual Communication of Speech Sounds to the Deaf: Comparison with Lipreading," Journal of Speech and Hearing Disorders, 28 (November, 1963), pp. 315-330.

[2] Gerald Johnson, "The Effects of Cutaneous Stimulation by Speech on Lipreading Performance," (unpublished Ph.D. dissertation, Michigan State University, 1963).

recoded into patterns for tactile reception by the human integument.

A major problem is inherent with the use of multiple vibrators, however. A significant masking effect causing considerable threshold elevation through any one of the vibrators has been described by Sherrick,[1] Pickett,[2] Gilson[3] and others. Gilson stated in a recent study that:

> It is quite clear that multiple maskers can indeed produce greater TE than a single masker. The highest TE with a single masker was 19.0 dB, while nearly 50% of the cases tested with multiple maskers resulted in TEs over 19.0 dB, the highest being 32.5 dB.[4]

Geldard communicated to the writer of the present study that the use of multiple stimulators for the purposes of this research would be premature and inadvisable. The study of the effects of masking is only in the initial stages of exploration. Further, he suggested that the procedure employed in the Vocoder described earlier

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[1] Carl E. Sherrick, "Effects of Double Simultaneous Stimulation of the Skin," The American Journal of Psychology, 77 (March, 1964), pp. 42-53.

[2] J. M. Pickett and B. H. Pickett, "Communication of Speech Sounds by a Tactual Vocoder," Journal of Speech and Hearing Research, 6 (September, 1963), pp. 207-222.

[3] R. D. Gilson, "Vibrotactile Masking: Effects of Multiple Maskers," Perception and Psychophysics, 5 (1969) pp. 131-132.

[4] *Ibid.*, p. 182. (TE refers to threshold elevation)

prohibits exact specification of the information that is being transmitted and received. For a direct transduction of the speech code and for the purposes of this study, he recommended the use of a single vibrator.[1]

In view of the foregoing discussion one might conclude that the significant potential of tactile stimulation for hearing handicapped persons is in providing supplemental clues for lipreading and residual auditory function. Although this approach appears to be of clear practical value, only limited basic data have been reported.

Not since the early work of Gault have researchers systematically studied the exact nature of the information that can be received as a result of direct vibromechanical transduction of the speech code. There have been certain problems and erroneous assumptions inhibiting this effort: (1) the need for a practical, efficient stimulus transmission system, (2) the lack of sufficient knowledge as to the capabilities of the cutaneous sensory receptors, (3) an erroneous assumption that the skin can serve as a direct substitute for the human inner ear, and (4) the

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[1] Telephone Communication with Frank A. Geldard, Ph.D., Professor of Psychology, Princeton University, December 30, 1969.

premature application of multiple stimulators without full knowledge of their inherent masking effects.

Now, with a perspective not possible several decades ago, due to advances in technology, a fresh look at the potentials of the human skin for communication purposes is viewed as timely and practical.

## Statement of Problem and Purpose of Study

This study seeks basic information relative to the functional utility of cutaneous reception of the speech code. The research was designed to provide answers to some basic psychophysical questions.

The purpose was to determine basic detection thresholds and gross discrimination characteristics for spoken English phonemes when presented to subjects through vibrotactile stimulation. The following questions were formulated to define the research:

1. What is the intensity level required for vibrotactile absolute thresholds for each of the English phonemes?
2. How do subjects describe the "distinctive features" for each of the English phonemes when they are asked to select characteristics from a closed set of descriptive adjectives?
3. With a specified constant stimulus level, can each of the English phonemes be distinguished as "same" or "different" from each other in paired comparisons?

A necessary requirement for completing the experiments was the development of a stimulus transduction system incorporating the latest technological advances. A system was designed and constructed to allow control over certain variables known to influence tactile reception. Of primary concern were: (1) specification of the frequency response limits of the system, including the vibromechanical stimulator; (2) control over the force applied at the contactor site on the skin; (3) a control over the size of the contactor area; (4) a system relatively free of lag with respect to "on-time" of the transmitted signal; and (5) a system employing a single, efficient vibrator.

## Importance of the Study

Research has shown that the cutaneous sensory receptors do not provide a reasonable substitute for the human ear. The theoretical basis for the research is that the skin receptors do provide a capability whereby significant information can be transmitted and discriminated. The idea that tactile sensory communication can serve as a supplement to auditory and visual communication has received recognition but only limited study. Tactile reception of the speech code has not been researched in

any systematic manner. Many basic questions remain unanswered. It was the intent of this study, therefore, to provide basic information relative to tactile stimulation by units of oral language.

The information obtained from this study is viewed as having practical application in increasing the aurally handicapped individual's success potential for receptive communication.

## Definitions

Vibrotactile stimulation: For this study, vibrotactile stimulation refers to the specific treatment to which the skin receptors are exposed when acoustic energy is transduced by electromechanical means.

Electromechanical transducer: The transducer of choice for this research was a piezoelectric ceramic material called a Bimorph. According to Geldard, the Bimorph is the latest and most efficient transducer developed for purposes such as this study. It has virtually no "on-time" lag and responds to frequencies above 20,000 Hz.[1] Its basic construction is a two ceramic plate sandwich-type structure.[2]

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[1] Ibid., December 30, 1969.

[2] A detailed description of the Bimorph is presented in Chapter III.

Absolute threshold of detectability: The threshold of detectability for a specified signal is the minimum effective stimulus level of the signal that is capable of evoking a tactual sensation 50 percent of the time.[1] In this case the signals are English phonemes presented by the traditional method of limits.

The psychophysical method of limits: Underwood has described the psychophysical method of choice for the determination of absolute thresholds. For half the trials the stimulus is initially clearly present and then is decreased gradually until the subject reports "not present." For the other trials the intensity is not of the magnitude to be perceived as present initially, and is increased gradually until the subject reports "present."

> For each trial a threshold measurement is obtained, momentary as it may be. But an average of a series of trials would give a fair estimate of the value which is detected 50 percent of the time.[2]

For the purposes of this research each subject was given eight trials. Four of these trials were of the ascending order, and four of the descending order.

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[1] Benton J. Underwood, "Thresholds," Chapter V, Experimental Psychology, (New York: Appleton-Century-Crofts, 1966), p. 134.

[2] Ibid, pp. 139-142.

*Distinctive features*: All the English phonemes may be broken down into the "inherent distinctive features which are the ultimate discrete signals" separating each phoneme from every other phoneme. In short, the distinctive features of a given phoneme are what make it a phoneme. Jakobson, Fant, and Halle describe ten dimensions that distinguish one phoneme from another. The judgments of the perceiver are basically binary: for example, he judges the phoneme as vowel or non-vowel, nasal or non-nasal, lax or tense, front or back, compact or diffuse, strident or mellow, and so on.[1] Obviously, these adjectives describe perceived auditory dimensions. The development of the distinctive features for tactile reception of the speech code was one of the purposes of this research.

*The method of paired comparisons*: The method of paired comparisons is what the name implies. Each stimulus in a group is paired, thus compared with every other stimulus. How many pairs need there be in order to meet the requirement that each phoneme is paired with every other phoneme in a group? The formula is $\frac{n(n-1)}{2}$. To

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[1] R. Jakobson, C. G. Fant and M. Halle, *Preliminaries to Speech Analysis*, (Cambridge: The M.I.T. Press, 1963), 69 pp.

consider judgments for each phoneme when compared to itself, additional paired stimuli need to be added.[1]

Phonemes: Phonemes are the basic linguistic units from which words are put together. They are the individual, inherently distinct speech sounds from which words are comprised. A phoneme in itself does not symbolize any concept or object. Phonemes in relation to other certain phonemes can form words. The phoneme /b/ for example, has no specific meaning, but in combination with other phonemes it can distinguish "beat" from "leap," "bell" from "sell," and so on.[2] More specifically, phonemes are "speech sound families." Symbols (phonetic symbols) are used to identify these families.

> Each symbol stands not for a separate sound but, rather, for a series of slightly varying sounds that includes all of the variations which are perceived acoustically as the sound under consideration.[3]

## Organization of the Research Report

Chapter I was organized to provide an introduction to the problem of tactile sensory communication. An

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[1] Underwood, Experimental Psychology, p. 197.

[2] P. B. Denes and E. N. Pinson, The Speech Chain, Bell Telephone Laboratories, (1964), p. 11.

[3] L. S. V. Judson and A. T. Weaver, Voice Science, (New York: Appleton-Century-Crofts, 2nd ed., 1965), p. 173.

overview of the potential and limitations of the tactile channel was presented. A rationale that led to the study was presented.

Chapter II consists of a comprehensive review of the literature relative to the topic of tactile communication.

Chapter III presents a description of the instrumentation, subjects, and research procedures utilized in the study.

Chapter IV provides the results of the evaluation of the data in terms of the questions generated in Chapter I.

Chapter V summarizes the research and presents the conclusions that can be drawn. Recommendations for future research are suggested.

# CHAPTER II

# REVIEW OF THE LITERATURE

## Introduction

While there has been disagreement over the capabilities of the tactile modality in communication, few researchers disagree that a potential does exist. Most of the research relative to tactile reception of the speech code has its foundation in the early work of Gault. Gault began his work in the early 1920's. Because he considered the cutaneous sensory receptors as a possible substitute for hearing, his major interest was in tactile discrimination of verbal stimuli. Gault was confronted with two major problems, however. First, no adequate tactile stimulus transmission system existed. Secondly, knowledge of the limitations of cutaneous perception was limited.

Following a period marked by the absence of additional research, Geldard and Pickett have generated renewed interest in the possibilities of the cutaneous channel. Von Bekesy's findings comparing audition and taction led Geldard and Pickett to consider tactile communication as a supplement, not a substitute, for auditory communication. Geldard's work has emphasized a recoding of verbal stimuli. Pickett has studied the use of tactile sensations as a supplement to lipreading.

The development of the current study is dependent upon the following topical interest areas: (1) comparisons between the auditory and tactile channels of sensory communication, (2) variables influencing tactile thresholds, (3) tactile stimulus transmission systems, and (4) cutaneous sensory reception of the speech code.

The remainder of this chapter presents a review of this literature.

### Comparisons Between the Auditory and Tactile Channels

Consistent with Gault's early optimism over the possibilities of tactile communication was his evaluation of the auditory and cutaneous senses. He considered the two senses to be fairly equal in their ability to receive vibratory stimuli. Further, he stated that it may be practical, when necessary, for taction to substitute for audition.[1]

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[1] R. H. Gault, "An Interpretation of Vibrotactile Phenomena," Journal of the Acoustical Society of America, 5 (1934), pp. 252-254.

Knudsen, in 1928, claimed that the finger tip was capable of receiving and differentially discriminating intensities with the same resolution as the inner ear.[1]

Goodfellow and Gridley, in separate studies, compared temporal discrimination phenomena of the finger tip and ear. They suggested the finger tip can detect differences in short intervals up to 90 percent of the accuracy of the ear.[2, 3]

In another comparative study between taction and audition, Jenkins found that for frequencies above 20 Hz the two modalities are "roughly analogous" in that both seem to project a sense of smooth vibration.[4]

Geldard has commented that in no case can the skin substitute for the ear in its ability to transmit the speech code. Although the cutaneous sensory receptors are capable of making temporal and spatial discriminations,

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[1] V. O. Knudsen, "Hearing with the Sense of Touch," Journal of General Psychology, 1 (1928), pp. 320-352.

[2] L. D. Goodfellow, "Comparison of Audition, Vision and Touch in the Discrimination of Short Intervals of Time," American Journal of Psychology, 46 (1934), pp. 243-258.

[3] P. Gridley, "The discrimination of Short Intervals of Time by Finger Tip and by Ear," American Journal of Psychology, 44 (1932), pp. 18-43.

[4] W. L. Jenkins, "Somesthesis," in Handbook of Experimental Psychology, S. S. Stevens, ed. (New York: John Wiley and Sons, Inc., 1951), p. 1177.

in neither case can they approach the ear in fineness of resolution.[1]

Hawkes and Loeb studied the vigilance ability of subjects for cutaneous and auditory stimuli. The stimuli consisted of sinusoidal waves delivered for 0.5 seconds with a rise time of one microsecond. They found response latency was longer for the cutaneous channel than for the auditory channel. In addition, signals presented tactually showed a greater number of failures of detection, and false responses were significantly more numerous.[2]

Georg von Bekesy has completed an extensive comparison between audition and taction.[3] His work on this topic has extended through the past 30 years.

Bekesy has demonstrated the phenomenon of traveling waves for both senses. Using stroboscopic observation he found that the skin surface under a vibrating needle shows traveling waves spreading out from a needle point in every direction and forming more or less concentric rings.

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[1] F. A. Geldard, "Some Neglected Possibilities of Communication," Science, 131:3413 (May 27, 1960), pp. 1583-1588.

[2] G. R. Hawkes, and M. Loeb, "Vigilance for Cutaneous and Auditory Signals," Journal of Auditory Research, 1 (1961), pp. 272-284.

[3] G. von Bekesy, "Similarities Between Hearing and Skin Sensations," The Psychological Review 66:1 (January, 1959), pp. 1-22.

These waves have little damping. Also, the waves' lengths decrease with an increase in vibratory frequency. In spite of this stroboscopic observation, the vibration is felt only under the tip of the stimulating contactor. "Thus it is clear that a large area under vibration can produce a sensation that is limited to a very small spot."[1] The maximum of vibrational amplitude for the skin is always under the tip of a given vibrator and results in a sensation of high localization. For the basilar membrane, however, the maximum vibrational amplitude changes its place along the membrane with the frequency of the stimulation. The high frequencies are localized near the stapes and the lows are localized near the apex. Bekesy has theorized that both these mechanical operations are mediated in the central nervous system in very similar ways.[2]

The similarity between loudness and the sensation of vibrational magnitude holds for only very sensitive parts of the human integument. For example, the finger tips are considered highly sensitive whereas the upper arm is not. Sensations on the upper arm increase much faster from threshold than does loudness. "For areas on the skin with high sensitivity, however, it is surprising

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[1] *Ibid.*, p. 7. [2] *Ibid.*, p. 5.

how great the similarity between loudness and the vibration sensation is."[1] The similarity is optimal when short clicks are used as stimuli. The employment of sinusoidal vibrations does not elicit the same response. Bekesy suggests this is so because the sensory receptors of the skin appear to react slower than receptors of the ear. For an instantaneous application of a sinusoidal vibration on the finger tip, more than one second is required for the signal to become fully established.

> In short, we can say that the nerves in the skin act more slowly than the auditory nerves, and, to obtain comparable effects, transients presented to the skin must be 5 to 10 times slower than those presented to the ear. On the other hand, the growth of sensation intensity of the finger tip is much like the growth of loudness in hearing.[2]

Geldard has found that there are about 15 intensive steps that can be discriminated, with only three to five as "absolutely identifiable" between 0.05 mm and 0.38 mm of amplitude at a frequency of 60 cycles. He found similar results with duration. There seems to be a possibility for some subjects to discriminate up to 25 just-noticeable steps, but the consistent response range over subjects is clearly between three and seven. The temporal durations selected for study spanned the range, 0.1 to 2.0 seconds.[3]

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[1] Ibid., p. 6. [2] Ibid., p. 7.

[3] Geldard, Science, 131:3413 (1960), p. 1585.

With respect to frequency sensitivity, the skin falls considerably short of the capability of the ear. The optimal frequency sensitivity of the skin is between 200 and 400 Hz, with lesser sensitivity up to 1000 Hz. From this point upward the threshold rises very rapidly, according to von Bekesy. The ear, however, is even more sensitive to a broader frequency range extending from around 200 Hz through 8,000 Hz.[1]

Geldard has found that maximum skin sensitivity occurs at 250 Hz. He prefers not to state an upper limit because of the technical difficulties of moving the skin at high frequencies.[2]

The Russians claim their research shows the Americans in error. Their studies show responses up to 2000 Hz which are useful for practical application.[3]

Wagner reported that for deaf persons the range lies between 5 and 1700 Hz with optimal sensitivity between

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[1] Bekesy, The Psychological Review, 66:1 (1959), p. 7.

[2] F. A. Geldard, "The Perception of Mechanical Vibration: I. History of a Controversy." Journal of General Psychology, 22 (1940), pp. 243-269.

[3] I. A. Sokolyanskiy, "On the Perception of Oral Speech by Blind Deaf-Mutes with the Aid of the Cutaneous Analysor," in Russian Translations on Speech and Hearing, ASHA Reports, Number 3, The American Speech and Hearing Association (March, 1968), pp. 220-227.

200 and 400 Hz. Below and above this range he advocates "sharply increased" amplification.[1]

Although disputed by Geldard[2] due to poor control of intensity interaction, Goodfellow, in 1933, reported a frequency sensitive range up to 8000 Hz.[3]

Knudsen sets the sensitivity to frequency from 16 Hz through 4000 Hz; although he did not investigate frequencies above 1600 Hz because of equipment limitations. Further, Knudsen found that vibratory rate must change as much as 15 to 30 percent before a difference is noticeable.[4]

Gault has reported varied specifications for frequency sensitivity. In two separate reports in one year, the upper frequency limit is set at 2000 and 3000 Hz respectively.[5, 6]

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[1] P. Wagner, "Investigations into Tactile Language," Neve Blätter für Taubstummenbildung, 15 (1961), pp. 82-109, cited in dsh abstracts, 2 (1962), pp. 226-227.

[2] Geldard, Science, 131:3413 (1960), p. 1585.

[3] L. D. Goodfellow, "The Sensitivity of the Fingertip to Vibrations of Various Frequency Levels," Journal of the Franklin Institute, 216 (1933), pp. 387-392.

[4] Knudsen, Journal of General Psychology, 1 (1928), pp. 320-352.

[5] R. H. Gault, "Hearing Through the Sense of Touch and Vibration," Journal of the Franklin Institute, 204 (1927), pp. 329-358.

[6] R. H. Gault, "On the Upper Limit of Vibrational Frequency That Can Be Recognized by Touch," Science, 65 (1927), pp. 403-404.

Geldard claims most of the early studies related to the frequency dimension are invalid. The failure to control for "subjective intensity" and the presence of troublesome transients originating from relatively crude instrumentation are the chief deficiencies.[1]

Goff implied she circumvented these problems by first assembling a band of equal-loudness stimuli which differed in frequency. Then she measured the $\Delta f$ systematically within each band throughout the obtainable frequency range. Her results showed that at frequencies below 70 Hz vibratory rate judgements are excellent. But, judgements become inconsistent rapidly as the frequency scale is ascended. For the frequency range vital to speech discrimination, 300-3000 Hz, the judgements are relatively poor.[2]

The subjective counterpart to frequency is another area that has received some study. The correspondence between vibratory rate and subjective pitch judgements is tenuous. Vibratory pitch is a joint function of both frequency and amplitude. This interaction has been described for the auditory channel. But the interaction is

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[1] Geldard, Science, 131-3413 (1960), p. 1586.

[2] G. D. Goff, Ph.D. Thesis, University of Virginia (1959), cited in Dissertation Abstracts, (1960).

relatively insignificant when compared to the interaction found in the cutaneous channel. In terms of audition, frequency is dominant, being only slightly affected by intensity increases.

> In hearing there are pitch changes of pure tones with increasing loudness, but they are of a much smaller magnitude. This difference indicates that the pitch sensation in hearing is not produced in the same way by the volleys as the pitch sensation on the skin.[1]

A further explanation of this is found in another statement by Bekesy:

> . . . the maximum of the vibration amplitude of the skin is always immediately under the vibrator for all frequencies, whereas on the basilar membrane the place of maximum vibration changes with frequency. Therefore, on the skin the pitch sensation is given entirely by the periodicity of the volleys in the nerves; in the ear pitch can be determined further by the place of the maximal stimulation along the basilar membrane.[2]

When the amplitude of a moderately strong 40 Hz signal is applied to the finger tip it undergoes a very marked downward shift of perceived vibratory rate. When the amplitude is decreased, the judged vibratory rate

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[1] G. von Bekesy, "Neural Volleys and the Similarity Between Some Sensations Produced by Tones and by Skin Vibration," Journal of the Acoustical Society of America, 29:10 (October, 1957), p. 1063.

[2] Ibid., p. 1059.

goes up perceptibly. Shifts of the order of three octaves have been reported by Bekesy.[1]

Two additional similarities between taction and audition have been described by Bekesy, localization and "funneling." If a sound is received by both ears at the same time, we localize the sound in the medial plane. If the sound reaches one ear before the other, we localize the sound to that side. Bekesy used clicks to demonstrate that when the sound delay is large from one ear to the other, the clicks do not fuse and we hear two separate clicks. As the time delay becomes smaller, the images of the two sides fuse together, the loudness increases and the sound appears in the ear opposite to the one receiving a delayed click.[2]

Bekesy has found an analogous situation in the skin sensations. To measure this phenomenon he used two vibrators both contacted to one arm about 12 cm. apart. As in hearing, when the time delay was large a separate sensation was felt under each vibrator or contactor. The

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[1] Bekesy, <u>Journal of the Accoustical Society of America</u>, 31 (1959), p. 338.

[2] Bekesy, <u>The Psychological Review</u>, 66:1 (January, 1959), pp. 1-22.

required time delay for fusion was about the same as for hearing.[1]

Bekesy used the word "funneling" in place of neural inhibition to describe the latter in cutaneous sensitivity. Employing five vibrators spaced about two centimeters apart in a line on the forearm he demonstrated the concept of funneling. His device incorporated a 20 Hz signal on one end with frequency progression up to 320 Hz on the opposite end vibrator. When the sensation magnitudes of all the vibrators were equated by amplitude adjustments, only the vibrator in the middle with its corresponding vibratory rate was perceived. Inhibition, therefore, is an incorrect concept for taction. Suppression is what occurs. But since the vibratory rates which were suppressed actually contributed to an increase in the strength of the central sensation, "funneling" is claimed by Bekesy as most descriptive.[2]

In summary, it has been demonstrated that taction cannot serve as a <u>substitute</u> for the ear. Numerous similarities have been discussed as well as highly

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[1] G. von Bekesy, "Sensations on the Skin Similar to Directiorial Hearing, Beats and Harmonics of the Ear," <u>Journal of the Acoustical Society of America</u>, 29:4 (April, 1957), pp. 489-501.

[2] Bekesy, <u>The Psychological Review</u>, 66:1 (1959), pp. 16-17.

significant differences. Many of the concepts that have evolved through the study of audition have a counterpart in taction. But in no case does taction equal or excel the ear in the critical dimensions for perception of the speech code. Comparative studies of the two modalities have explored the concepts of intensity, frequency, duration, vigilance, traveling waves, loudness, pitch, localization, and neural inhibition or funneling. While tactile sensitivity has a capability with each dimension, the information transmitted to the nervous system is crudely molar compared to the sophisticated, molecular capability of the human inner ear.

## Variables Influencing Vibrotactile Thresholds

It is well known that in order to fire off a sensory endorgan, the energy impinged on it must reach a certain level. This level is referred to as the "threshold of excitation." Measured in ergs, the mean sensory thresholds of the skin are much higher than those of vision and audition. Taction requires about $10^8$ to $10^{12}$ as much energy for arousal.[1]

In that the first question of this study pertains to thresholds of detectability for spoken phonemes,

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[1] D. Sinclair, Cutaneous Sensation (New York: Oxford University Press, 1967), p. 157.

literature regarding factors affecting cutaneous thresholds is relevant to the scope of the present study. Most of the literature evaluates threshold as a function of body site. Other variables influencing thresholds are contactor size, multiple vibrators, applied pressure at contactor point, adaptation, and recruitment.

## Body Site

There is considerable research which supports the belief that the finger tips are the most sensitive parts of the human body to vibratory energy. Roth found the eyelids least sensitive and the fingertips most sensitive.[1]

On comparing the sensitivity of various regions of the forearm and hand, Gilmer described the fatty portions of the palmer side of the hand and the finger tips as possessing the highest sensitivity.[2]

Research completed by Ahrens demonstrated that the upper extremities are more sensitive than the lower

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[1] A. Roth, "Measurement of Vibration Sense," War Medicine, 4 (1943), pp. 280-282.

[2] B. V. H. Gilmer, "The Measurement of the Sensitivity of the Skin to Mechanical Vibration," Journal of General Psychology, 13 (1935), pp. 42-61.

extremities. Further, the distal aspects of the extremities are the most sensitive.[1]

This finding was also reported by Bekesy. He used a vibrating needle to evaluate the relative sensitivities of various loci from the shoulder to the finger tip. Sensitivity was found to decrease as stimulation was ascended on the limb.[2]

Sherrick and Geldard, noting that most studies in cutaneous sensory communication used the finger tips for stimulation, studied the sensitivity of other body loci. They found that sites on the upper torso are generally inadequate because of an uncontrollable interaction with hearing by bone conduction.

> It is surprising how readily a low frequency signal comes through to the cochlea from bony areas like the rib cage, shoulders, neck, and head region. Since so much of our earlier communication work had been carried out with the broad expanse of the chest as the stimulation site, it was natural to continue its use in the selection of loci . . . But 115 dB SPL of steady white noise delivered by phones to the ears would not suppress the hearing--and observers insisted it was hearing-- of a 200 millesecond burst of 60 Hz mechanical vibration at 15 dB (sensation level). This does not happen on the fleshy portions of limbs if sufficiently far removed from bony protuberances

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[1] R. S. Ahrens, "A Study of the Vibratory Sensation," Archives of Neurology and Psychiatry, 14 (1925), p. 793.

[2] G. von Bekesy, The Psychological Review, 66:1 (January, 1959), p. 6.

> nor does it happen on the abdomen. Very much lower masking levels are entirely adequate.[1]

Ten other body loci were found to be sensitive enough for tactile communication purposes. The upper and lower thigh area, the upper and lower calf, and positions on the forearm are satisfactory. When the body data were compared to data regarding finger tip sensitivity, in no case was a body site superior to the sensitivity of the finger tips.[2]

A comparison of the discriminability of patterns applied to the fingers and the discriminability of patterns applied to the body was made by Gilson.[3] The patterns were presented to the ten body loci described by Sherrick and Geldard. The ten finger tips provided the other contactor sites. One thousand different patterns were presented in alternating sequences over the 20 sites for comparison. The initial results indicated 125 percent more errors on the fingers. When the vibrators for the finger tips were

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[1] F. A. Geldard, "Pattern Perception by the Skin," Chapter 13 in <u>The Skin Senses</u>, D. R. Kenshals, ed. (Springfield, Illinois: Charles C. Thomas, 1968), p. 305.

[2] F. A. Geldard and C. E. Sherrick, "Multiple Cutaneous Stimulation: the Discrimination of Vibratory Patterns," <u>Journal of Acoustical Society of America</u>, 37 (1965), pp. 797-801.

[3] R. D. Gilson, "Some Factors Affecting the Spatial Discrimination of Vibrotactile Patterns," <u>Perception and Psychophysics</u>, 3:2B (1968), pp. 131-136.

modified in size and the arrangement of contactor sites was shifted to noncorresponding points, a substantial abatement of errors was realized. Further, when these results were compared to the body data, there was no statistically significant difference found.

Shewchuk and Zubek studied the sensitivity of various skin areas measured by means of intermittent stimulation. The technique used was an interrupted air stream. The sites stimulated were the tongue, lips, cheeks, forehead, neck, tip of the index finger, thumb, back of the hand, forearm and upper arm. The sensitivity for the lips, tongue and fingers was greater than for the other body locations.[1]

Several studies have supported the notion that the regions of the skin most sensitive to mechanical vibration are those loci which are also most sensitive to pressure.[2, 3] It has been hypothesized that vibratory

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[1] L. A. Shewchuk, and J. P. Zubek, "Discriminatory Ability of Various Skin Areas as Measured by a Technique of Intermittent Stimulation," Canadian Journal of Psychology, 14 (1960), pp. 244-248.

[2] F. A. Geldard, "The Perception of Mechanical Vibration: I. History of a Controversy," Journal of General Psychology, 22 (1940), pp. 281-289.

[3] B. H. Gilmer, "The Relation of Vibratory Sensitivity to Pressure," Journal of Experimental Psychology, 21 (1937), pp. 456-463.

sensations form a perceptual pattern of feeling of which pressure is but another temporal expression. Geldard has noted that vibratory thresholds for a single frequency of 60 Hz is significantly lowered by increases in applied pressure. He suggests that the pressure of the tactile stimulation is a form of energy that distorts the cutaneous tissue, and the sensation of being stimulated arises from variations of this distortion.[1]

## Pressure on Contactor

The amount of pressure that a contactor exerts on the skin has been specified as an important variable by Verrillo. He studied the effects of five contactor heights (-0.5, 0, +0.5, +1.0, and +1.5 mm) with a standard 0.113 $cm^2$ size contactor. Four test frequencies were employed: 40, 80, 160 and 320 Hz. His results show that as the contactor is pressed into the cutaneous tissue, the threshold for vibration decreases systematically. At the upper end of threshold shift, for example, a 320 Hz signal presented at a contactor height of 1.5 mm produced a 12 dB shift.

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[1] B. V. H. Gilmer, "The Measurement of the Sensitivity of the Skin to Mechanical Vibration," Journal of General Psychology, 13 (1935), pp. 42-61.

Verrillo's data clearly indicated that thresholds for vibration decrease in direct proportion to the extent of protrusion by the contactor.[1]

These results support the findings of Cohen and Lindley in 1938 and Babkin, Rozen, Tumarkina, and Chernyak in 1961.[2, 3]

Multiple Vibrators

Geldard discourages using the finger tips for multiple stimulation such as are incorporated in the design of some of the present day stimulus transmission systems.

> . . . the skin areas sharing the same spinal segment interact strongly with one another in some contralateral stimulating situations. It is pretty clear that the only circumstance that would avoid the threat of such interaction, in the case of the fingers, would be a sample of monsters endowed with fingers located at noncorresponding body sites!"[4]

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[1] R. T. Verrillo, "Effect of Spatial Parameters on the Vibrotactile Threshold," Journal of Experimental Psychology, 71:4 (1966), p. 573.

[2] L. H. Cohen and S. B. Lindley, "Studies in Vibratory Sensibility," American Journal of Psychology, 51 (1938), pp. 44-63.

[3] V. P. Babkin, et. al., "Investigation of Vibration Sensitivity and Factors Affecting It," Biophysics, 6 (1961), pp. 39-43.

[4] Goldard, The Skin Senses, (Springfield, Illinois: Charles C. Thomas, 1968), p. 309.

To energize all fingers simultaneously is to force "two handfuls of vibration."[1]

Gilson further studied the effects of using the finger tips for simultaneous multiple stimulation. When all ten vibrators were turned on the subjects in this study also perceived "two handfuls of vibration." The subjects complained that the vibratory stimuli were so diffuse that they were perceived as not even being on the hands, but surrounding them. The fewer the vibrators, the less vague were the localizations. The author concluded that the employment of multiple vibrators on the finger tips presents problems that are currently insurmountable.[2]

Sherrick compared the effects of double simultaneous stimulation among the left index finger tip, the left palm at the base of the thumb, and the right little finger. Each of these areas was paired with the right index finger in order to present the desired double stimulation. Equal intensities and frequencies were employed. All possible double stimulation comparisons were evaluated. The results showed that there are the phenomena of ipsolateral and contralateral masking. The effectiveness of a contralateral

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[1] _Ibid_., p. 310.

[2] R. D. Gilson, "Some Factors Affecting the Spatial Discrimination of Vibrotactile Patterns," _Perception and Psychophysics_, 3:2B (1968), pp. 131-136.

masking function decreases significantly when the sensation level is beyond 40 dB. Further, ipsolateral masking causes the greater masking effect, but rises at a slower rate than for the auditory channel.[1]

Gilson has described another problem in using multiple stimulators. Threshold elevations were found when simultaneous stimuli were presented over various body loci. Various combinations and numbers of multiple vibrators were placed on sites of the trunk of the body. In one case a threshold elevation of 19 dB was found with only a single competing vibrator. Further, when six to eight were used simultaneously, nearly 50 percent of the cases tested resulted in threshold elevations over 19 dB, the highest being 32.5 dB.[2]

Alluisi, Morgan and Hawkes found similar results. In their study they presented simultaneous stimulation using six loci on both of the shoulders, elbows and wrists. This resulted in a complete suppression of the sensation at the elbow. The elimination of the stimulation at either

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[1] C. E. Sherrick, "Effects of Double Simultaneous Stimulation of the Skin," The American Journal of Psychology, 77 (March, 1964), pp. 42-53.

[2] R. D. Gilson, "Vibrotactile Masking: Effects of Multiple Maskers," Perception and Psychophysics, 5:3 (1969), pp. 181-182.

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the shoulder or wrist allowed a return of the sensation at the elbow.[1]

Contactor Size

The influence of contactor size on frequency-intensity functions has been reported by Verrillo. When small contactors are used (0.005 and 0.02 $cm^2$) the threshold curves are independent of frequency, and therefore, flat. A very pronounced effect is found when the contactor is large (2.9 $cm^2$). The curve is (U) shaped with maximum sensitivity at 250 Hz.

> It is obvious that we are observing two distinct modes of response; one in which the receptor system is sensitive to changes in frequency, and another that is independent of frequency. The point at which the frequency-dependent system determines the shape of the curve is a function of the contactor size. For very small contactors the entire function is determined by those receptors not affected by frequency changes.[2]

For frequencies above 40 Hz the slope of the curve is -3 dB per doubling of the contactor area, indicating that a summation of energy is taking place over the area of the

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[1] E. A. Alluisi, B. Morgan and G. Hawkes, "Masking of Cutaneous Sensations in Multiple Stimulus Presentation," Perceptual and Motor Skills, 20 (1965), pp. 39-45.

[2] R. T. Verrillo, "Effect of Spatial Parameters on the Vibrotactile Threshold," Journal of Experimental Psychology, 71:4 (1966), pp. 570-575.

contactor. There is no summation, however, for 40 Hz and lower.[1]

> In hearing, Zwicher, Flottorp, and Stevens (1957) also obtained a -3 dB slope when they measured constant loudness of tones and noise as a function of the width of the energy band of the stimulus. An increase in the bandwidth of an auditory stimulus can be considered the direct correlate of an increase in the area of stimulation along the basilar membrane. It was reasonable, therefore, to expect that doubling the area of stimulation in vibrotactile experiments would also produce a reduction in absolute threshold of about 3 dB.[2]

Thus, an inverse relationship exists between the vibrotactile threshold and the contactor area, having a slope of 3 dB per doubling of area.

Using four contactor sizes ranging from 0.005 $cm^2$ to 2.9 $cm^2$, Verrillo investigated vibrotactile threshold shift as a function of pulse repetition rate. For pulse rates of five per second and less, no shift in threshold was found for any of the variable size contactors. At a pulse rate of 10 per second, a shift of 5 dB was found using the largest contactor. No shift was found for the other three. Further, as the pulse rate was increased up to 100 per second only the largest contactor (2.9 $cm^2$)

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[1] R. T. Verrillo, "Effect of Contactor Area on the Vibrotactile Threshold," Journal of the Acoustical Society of America, 37 (1963), p. 1962.

[2] Verrillo, Journal of Experimental Psychology, 71:4 (1966), pp. 570-575.

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effected a shift (17 dB) of any significance. Verrillo concluded that the largest contactor produced considerable summation, whereas the other three produced relatively little. The smallest contactor produced no summation.[1]

## Adaptation

Adaptation of the tactile modality is another variable affecting threshold sensitivity. Wedell and Cumming found adaptation to be a function of both amplitude and frequency. The loss of sensitivity is greater for the higher frequencies. Further, when stimulation is sustained and intensities are augmented relative sensitivity decreases. Specifically, they found threshold sensitivity reduced from 5 dB to 15 dB following three minutes of sustained stimulation at a given frequency. When an immediately following stimulation involved a higher frequency the same loss of sensitivity was demonstrated. This finding did not hold when a lower frequency was employed subsequent to a higher frequency.[2]

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[1] R. T. Verrillo, "Temporal Summation and Vibrotactile Sensitivity," _Journal of the Acoustical Society of America_, 37 (1965), pp. 843-850

[2] C. H. Wedell and S. B. Cummings, "Fatigue of the Vibratory Sense," _Journal of Experimental Psychology_, 22 (1938), pp. 429-438.

Using a technique of double simultaneous vibratory stimulation, Van Buskirk and Calloway offered some observations on adaptation of the cutaneous sensory receptors. Three forms of adaptation were found: (1) Absolute adaptation to a weak supra-threshold stimulus. (2) Elevation of threshold at the site of a previous strong supra-threshold stimulation. (3) Absolute adaptation to a weak supra-threshold stimulus induced by strong contralateral stimulation.

> Vibratory sensation is the result of a constantly changing stimulus. Physical adjustment of peripheral sense organs cannot explain decreasing sensitivity to a vibrating stimulus. When adaptation occurs it must be due to factors operating within the nervous system.[1]

Hahn asserts that tactile adaptation is more correctly identified by using the words "stimulus failure." With reference to previous studies he stated: "It thus appeared that what had been called tactile adaptation did not actually reflect a change in receptor sensitivity, but instead resulted from tissue elasticity opposing with steadily increasing force of the pressure stimulus."[2] Further, Hahn stated that a review of the studies completed

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[1] C. Van Buskirk and E. Calloway, III, "Observations on Vibratory Thresholds," <u>Confinia Neurologica</u> 16:6 (1956) pp. 301-307.

[2] J. F. Hahn, "Tactile Adaptation," in <u>The Skin Senses</u>, D. R. Kenshalo, ed., (Springfield, Illinois: Charles C. Thomas, 1968), p. 332.

in this area led him to believe that the words stimulus, failure, adaptation, accommodation, fatigue and equilibration have been used interchangeably whereas none of the distinctions among the phenomena have been demonstrated.[1]

## Recruitment

A potential problem of recruitment also exists in the tactile modality. Geldard has expressed the present state of knowledge in this area:

> In audition 15 dB SL would be well below a whisper, scarcely more than the sound of a well-dropped pin. But the skin is not the ear, even though in some respects it behaves very much like certain damaged ears. It recruits in a most remarkable fashion. Move vibratory amplitude up from absolute threshold in small steps and loudness bounds rapidly ahead. The skin has a relatively short dynamic range as compared with that of the ear. Just what the detailed metrics of the situation are it would be nice to know.[2]

## Summary

In view of the literature presented regarding factors influencing vibrotactile thresholds, the following statements can be made. (1) Body loci vary significantly in sensitivity to vibrotactile stimulation. Most researchers agree that the finger tips are most sensitive. Care must be taken in choosing sites on the upper torso because of

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[1] Ibid., p. 329.

[2] Geldard, The Skin Senses, D. R. Kenshalo, ed., (Springfield, Illinois: Charles C. Thomas, 1968), p. 305.

intervention by the auditory channel. (2) Thresholds decrease in direct proportion to the extent of applied pressure or protrusion by the contactor. (3) The use of multiple simultaneous stimulation causes significant threshold elevations due to the masking effects caused by the competing stimuli. (4) When contactors are large (2.9 $cm^2$) there is an inverse relationship between vibrotactile threshold and the contactor area, having a slope of 3 dB per doubling of area. When contactors are small (0.005-0.02 $cm^2$) the threshold curves are independent of frequency. (5) The role of adaptation is not clear. There is some evidence that adaptation occurs frequently at high frequencies and when stimulation is strong and sustained. (6) The phenomenon of recruitment is present, although the metrics are unknown.

## Vibrotactile Stimulus Transmission Systems

In the early 1920's Gault first reported experiments in transmitting messages to be received through the skin. These first efforts employed equipment consisting of a long speaking tube positioned through several walls. A subject sat at one end of the apparatus and made gross

discriminations between various tuning fork vibrations and between speech sounds.[1]

Gault next employed the use of a disk shaped receiver similar to the ear piece of a telephone receiver. A speaker was placed in a room 35 feet removed. His messages were amplified by a three tube amplifier and received on the finger tips of a subject.[2]

More refined instrumentation was developed in 1928. The Bell Telephone Laboratories assisted Gault and his research through the construction of the Teletactor. Speech energy was divided into five frequency bands, amplified and introduced to each of the five fingers of one hand by simple vibrators. Each vibrator received the output of a speech filter which passed only a portion of the speech frequencies. The filters covered a range from 0 to 3000 Hz.[3] Pickett has commented on a major limitation of this system.

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[1] R. H. Gault, "Progress in Experiments on Tactual Interpretation of Oral Speech," Journal of Abnormal and Social Psychology, 19 (1924), pp. 155-159.

[2] R. H. Gault, "Control Experiments in Relation to Identification of Speech Sounds by Aid of Tactual Cues," Journal of Abnormal and Social Psychology, 21 (1926), pp. 4-13.

[3] R. H. Gault and G. W. Crane, "Tactual Patterns from Certain Vowel Qualities Instrumentally Communicated from a Speaker to a Subject's Fingers," Journal of General Psychology, 1 (1928), pp. 353-359.

> One difficulty with this system is the fact that the sensitive frequency range of vibratory sensation is only about 75 to 800 cps when expressed as the range over which threshold sensitivity remains within 20 dB of the most sensitive region.[1]

Gault used the Teletactor to complete several studies of vibrotactile transmission of the speech code. This research will be discussed in the last section of this chapter.

Keidel stored speech on magnetic tape which was recorded at a rate of 15 inches per second. The playback speed was slowed down to a factor of about eight, or two inches per second. Thus, the speech frequency range of 300 to 3000 Hz was shifted downward to a range of 40 to 400 Hz. The"slowed down" tape was fed into a mechanical vibrator based on a model described by Bekesy.

> The physical features of the model permit spatial dispersion of the frequencies between 40 and 400 cps so that the surface of the model sensitive to 40 cps vibrates 30 cm distant from the point of vibration for 400 cps. When the volar side of the forearm is brought into contact with the vibrating surface of the model, each frequency excites another point of the skin within a length of 30 cm.[2]

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[1] J. M. Pickett and B. H. Pickett, "Communication of Speech Sounds by a Tactual Vocoder," Journal of Speech and Hearing Research, 6:3 (September, 1963), pp. 207-222.

[2] W. D. Keidel, "Note on a New System for Vibratory Communication," Perceptual and Motor Skills, 8 (1958), p. 250.

As alluded to earlier, Bekesy's apparatus was an enlarged mechanical model of the inner ear. With this device the skin of the forearm simulated the nerve supply of the basilar membrane of the inner ear. His purpose in designing this model was to further his study on the traveling wave theory of hearing. A brief description is as follows:

> The model for the traveling waves was a plastic tube case around a brass tube with a slit. The tube was filled with fluid. A vibrating piston set the fluid inside the tube in motion, and forces in the fluid produced waves that traveled from the hand to the elbow.[1]

In 1936 Dudley devised the forerunner of the present-day Vocoder. Similar to Keidel's notion, the frequencies were transposed downward, although the technique was different. With the Vocoder, a reduced set of signals represents the energy fluctuations in a corresponding set of speech frequency bands. The signals are transposed and transmitted over narrow low frequency bands which are most sensitive for tactile reception. With the Vocoder the speech signals can be presented visually or tactually.[2]

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[1] Bekesy, <u>Experiments in Hearing</u>, (New York: McGraw-Hill Book Company, 1960), p. 546.

[2] H. W. Dudley, "The Vocoder," <u>Bell Laboratory Record</u>, 18 (1936), pp. 122-126.

FELIX, a refinement of the Vocoder, was built by Levine and his colleagues at the Massachusetts Institute of Technology. Its operation is based on the division of the speech frequency spectrum into seven frequency bands with potential variations in amplitude. Pickett has described FELIX as follows:

> First it divided the speech spectrum into seven frequency bands and derived a rough measure of the energy in each band. These fluctuating measures were then presented to the skin of the receiving subject. They were presented in the form of amplitude variations of effective tactual stimuli, either vibratory or electrical.[1]

Both FELIX and the Vocoder were designed to stimulate the cutaneous sensory receptors of the finger tips.

The present-day Vocoder was developed by Fant and his associates at the Speech Transmission Laboratory of the Royal Institute of Technology in Stockholm. The apparatus is a ten channel, two-hand model. Two hands (right and left) are actually drawn on two box-like structures. The stimuli are presented by bone conduction transducers, the lowest frequency being presented to the little finger on the left hand and proceeding to the higher frequencies on the right hand. Pickett has brought the Vocoder to the United States for additional study. He describes the apparatus as follows:

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[1] Pickett and Pickett, Journal of Speech and Hearing Research, 6:3 (1963), p. 208.

> The speech signal was first passed through a differentiator to provide high frequency emphasis of 6 dB/octave. The signal was then divided by overlapping filters into ten channels having center frequencies of 210, 400, 580, 830, 1050, 1800, 2250, 3320, 5800, and 7700 cps. The response curves of the channel filters were triangular with sides having slopes that approached 12 dB/octave. The output signal from each channel was rectified and smoothed to yield a control voltage. Each of ten control voltages modulated the amplitude of a 300 cps sinusoidal signal. The varying 300-cycle signals were amplified, adjusted for channel sensitivity, and then led to 10 bone-conduction transducers which served as vibrators. The vibrators stimulated the ventral tips of the subject's firgers Proceeding from left to right across the dorsal view of the two hands, the frequency channels were presented to fingers in order beginning with the lowest channel and proceeding to the highest channel. The receiving subject merely placed his finger tips on the vibrators to feel the vibratory patterns.[1]

Johnson constructed a "Cutaneous Speech Transmission System" which consisted of four loudspeakers, two inches in diameter, directly contacting the forearm of a subject. Speech signals were amplified and transmitted through the speakers. On the face of each speaker a Pellon fabric was attached by glue. The vibrations activated the center of the membrane and produced an elliptical vibratory pattern.[2]

Because of the many limitations of the cutaneous sensory receptors, the limited frequency response capabilities and the masking effects of multiple vibrators applied to the fingers, Geldard advocates recoding verbal

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[1] *Ibid.*, p. 209.

[2] Johnson, Doctoral Dissertation, 1963.

stimuli. Using the dimensions of loci, duration and intensity, verbal or written information is transposed to patterns over ten loci on the human integument. Speech sounds or phonemes are not used in this transposition. Each letter of the alphabet is coded into a pattern of stimulation. A 60 Hz sinusoidal signal of varying intensities and durations provides the basic stimulus. Geldard refers to this procedure as "vibratese language."[1] The vibrator presently used in this system is the Bimorph, which is the vibrator of choice for this study.

In addition to vibrotactile stimulus transmission systems, electrodes and even electric current have been employed in cutaneous experiments. To date, however, no practical system has been developed using electrocutaneous stimulation.[2] A problem of unpleasant or painful sensations has not been completely circumvented.

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[1] Geldard, Sensory Communication, (Cambridge, Massachusetts: The M. I. T. Press, 1961), Chapter 4.

[2] Geldard, Science, 131 (1960), pp. 1583-1588.

Nonetheless, numerous exploratory experiments have been completed.[1, 2, 3, 4]

## Cutaneous Sensory Reception of the Speech Code

Most of the early studies employing speech stimuli for tactile reception utilized Gault's Teletactor.

Gault's first subject was a 28 year old deaf female. At the end of 200 hours of practice with the Teletactor, this subject could distinguish about 50 percent of a list of 172 monosyllabic words.[5]

In another study Gault submitted a subject to 28 half-hour training sessions. Subsequent to training the subject could judge, with about 75 percent accuracy, which one of ten short sentences had been presented to the

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[1] Attell B. Anderson and W. A. Munson, "Electrical Excitation of Nerves in the Skin at Audio-frequencies," Journal of the Acoustical Society of America, 23 (1951), pp. 115-159.

[2] B. V. Gilmer, "Toward Cutaneous Electro-Pulse Communication," The Journal of Psychology, 52 (1961), pp. 215-216.

[3] G. R. Hawkes, "Potential Answers to Communication Problems," Aerospace Medicine, 33 (1962), p. 658.

[4] M. Nelson, "Electrocutaneous Perception of Speech Sounds," A. M. A. Archives of Otolaryngology, 69 (April, 1959), pp. 445-448.

[5] Gault, Journal of Abnormal and Social Psychology, 19 (1924), pp. 155-159.

cutaneous sensory receptors. A change of speakers or a reduced rate of speaking significantly altered these results, however.[1]

Following extensive, systematic practice using the Teletactor, Gault found that subjects could recognize vowels, dipthongs, consonants and short sentences with with reasonable efficiency.[2]

The Teletactor was also used by Cloud in a study employing eight deaf subjects. Upon the completion of one year of training for his subjects, the following conclusions were stated:

> (1) The teletactor proved to be an aid in tone production, (2) it offered an easy means of distinguishing between long and short vowels and (3) it affords a convenient means for pointing out silent and unvoiced elements, (4) accent in a combination of syllables is more easily developed by aid of the teletactor than without it, (5) the omission of an element or a syllable when it should be vocalized, or its vocalization when it should be silent, is more easily corrected by the use of the instrument than otherwise, (6) the pupils that used the teletactor have a much smoother speech than is usually found in deaf children of their age.[3]

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[1] Gault, Journal of Applied Psychology, 10 (1926), pp. 75-88.

[2] R. H. Gault, "Hearing Through the Sense of Touch and Vibration," Journal of the Franklin Institute, 204 (1927), pp. 329-358.

[3] Cloud, American Annals of the Deaf, 78 (1933), pp. 200-203.

Success in aiding young deaf students learn speech was also reported.[1, 2, 3]

Nelson compared one and two electrode systems in a vowel sound discrimination task. Ten normal hearing subjects were presented pairs of vowels for a same-different response set. He concluded that most normal hearing subjects could differentiate vowel sounds cutaneously. The two electrode system was found to be superior to the one electrode system. Significant differences were reported among subjects, however.[4]

A Goodman "Shake-Table" vibrator was employed in a study by Myers. This single vibrator was used to stimulate the middle three fingers and thumb of each subject. Myers used 16 single words for tactile

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[1] L. E. Dean, "Experiments in the Academic Education of Adolescent Deaf Pupils," American Annals of the Deaf, 79 (1934), pp. 292-305.

[2] D. T. Cloud, "Some Results from the Use of the Gault-Teletactor," American Annals of the Deaf, 78 (1933), pp. 200-204.

[3] R. H. Gault, "Extension of the Uses of Touch for the Deaf," School and Society, 23 (1926), pp. 368-370.

[4] Nelson, A. M. A. Archives of Otolaryngology, 69 (1959), pp. 445-448.

discrimination. An average of 91 percent accuracy was claimed after eight training sessions.[1]

In 1962, Pickett and Pickett evaluated the potential of the ten channel tactile Vocoder to transmit speech information. One male and one female speaker presented 15 vowel sounds for discrimination tasks. Consistent discrimination for the pairs /e-o/ and /e-ɝ / was found. Good success was found for /i-I, /u-o/ and /o-a/; moderate success for /a-ʌ/, /o-u/, and /o-ʌ/; and fair success for /i-e/, /e-ɛ/, /ɛ-æ/, and /æ-a/. Further, vowel sounds of relatively longer durations elicited more consistent responses.

A second part of this study compared 19 consonant pairs. The /s-t/ pair elicited a 99.5 percentage of discrimination, whereas the /p-b/ combination showed only a 22 percent discrimination capability.

The authors concluded that the employment of ten fingers with vibrotactile stimulation presents two basic problems. First, the masking effects are claimed to obscure certain discriminations. The /i, I, e/ sounds

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[1] R. D. Myers, "A Study in the Development of a Tactual Communication System," Symposium: Air Force Human Engineering Personnel and Training Research, (Glen Finch, ed., Washington, D. C., Publication 783, National Academy of Sciences, National Research Council, 1960), pp. 238-243.

were significantly influenced in this study. Also, in some cases two or more adjacent vibrators were felt to vibrate for each vowel.[1]

> Vibratory impressions, from simultaneous stimulation of two or more fingers, are not very distinct as to spatial pattern of stimulation, even when the pattern extends over both hands.[2]

Secondly, the authors admit that immobilizing all fingers of both hands is, at best, cumbersome. The Picketts suggest that three or four discrete loci may be the maximum number that can be used profitably.[3]

Considerable success has been reported when taction is combined with vision in sensory communication. Gault reported three studies which showed lipreading success was significantly enhanced when tactile information was conjointly presented with visual information.

In the first study an increment of 20 percent was found when lipreading was used with the Teletactor.[4] A second experiment showed a 50 percent improvement when

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[1] Pickett and Pickett, Journal of Speech and Hearing Research, 6:3 (September, 1963), pp. 207-222.

[2] Ibid., p. 214.

[3] Ibid., p. 220.

[4] R. H. Gault, "A Partial Analysis of the Effects of Tactual-Visual Stimulation by Spoken Language," Journal of the Franklin Institute, 209 (1930), pp. 437-458.

taction was used as a supplement to vision.[1] For a more difficult task, Gault used isolated monosyllabic words for lipreading by subjects. Combined stimulation produced a 30 percent increase in lipreading scores. When sentences were employed with the same subjects, a 100 percent improvement was reported.[2]

Ilieva also used the Teletactor in a combined stimulation study. A 77 percent improvement was found in the visual-tactile situation.[3]

## Summary

The relevant literature reveals the following salient information:

### Taction Compared to Audition

(1) While there are numerous similarities between taction and audition, the magnitude of the differences,

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[1] R. H. Gault, "On the Identification of Certain Vowel and Consonantal Elements in Words by Their Tactual Qualities and by Their Visual Qualities as Seen by the Lipreader," Journal of Abnormal and Social Psychology, 22 (1927), pp. 33-39.

[2] R. H. Gault, "On the Effect of Simultaneous Tactual-Visual Stimulation in Relation to the Interpretation of Speech," Journal of Abnormal and Social Psychology, 25 (1930), pp. 498-517.

[3] M. L. Ilieva, "On the Detection of Variations in Tempo of Speech by Visual, Tactual, and Visual-Tactual Cues," Journal of General Psychology, 7 (1934), pp. 100-109.

however, suggest that taction cannot serve as a substitute for the ear.

(2) The auditory concepts for intensity, frequency, duration, traveling waves, localization, recruitment and neural inhibition all have their counterparts in the tactile modality.

(3) While tactile sensitivity has a capability with each of these dimensions, the information transmitted to the nervous system is crudely molar compared to the sophisticated molecular capability of the human ear.

(4) Of primary significance is the limited capability of the skin to receive the frequencies within the critical speech range. The perception of vibratory rate for very low frequencies (100-300 Hz) is very good. But for the higher frequencies, judgements are relatively poor.

## Variables Influencing Vibrotactile Thresholds

(1) Body loci vary significantly in sensitivity to vibrotactile stimulation. Most researchers agree that the finger tips are most sensitive. Care must be taken in choosing sites on the upper torso because of intervention by the auditory channel.

(2) Thresholds decrease in direct proportion to the extent of applied pressure or protrusion by the contactor.

(3) The use of multiple simultaneous stimulation causes significant threshold elevations due to the masking effects caused by the competing stimuli.

(4) When contactors are large (2.9 $cm^2$) there is an inverse relationship between vibrotactile threshold and the contactor area, having a slope of 3 dB per doubling of area. When the contactors are small the threshold curves are independent of frequency.

(5) The role of adaptation is not clear. There is some evidence that adaptation occurs frequently at high frequencies and when stimulation is strong and sustained.

(6) The phenomenon of recruitment is present, although the metrics are unknown.

## Stimulus Transmission Systems

(1) Several vibromechanical stimulus transmission systems have been employed in research studies. Telephone receivers, small loudspeakers, bone conduction vibrators, simple vibrators and the more complicated multiple-vibrator devices such as the Teletactor, FELIX and the Vocoder are examples.

(2) Most stimulus transmission systems have employed multiple vibrators to achieve a downward frequency transposition. Recent research shows a significant

masking effect under these conditions, obscuring the effectiveness of the devices.

(3) Electrodes and electric current have been used in some experiments. No practical advantage in this approach has been demonstrated. The problem of unpleasant or painful sensations has not been completely circumvented.

## Cutaneous Sensory Reception of the Speech Code

(1) Only questionable success can be attributed to the early efforts in the 1920's to receive the speech code through the tactile modality. Limited information on the capabilities of the cutaneous sensory receptors and crude instrumentation restricted meaningful observations.

(2) Several years elapsed before a renewed interest was generated in transmitting speech signals to the skin. The current approach asserts that taction can serve as a supplement to visual and residual auditory communication. Research by Pickett, Johnson and Guberina lends support for this view. The results show that lipreading performance is significantly improved when tactile and visual information is simultaneously received.

(3) The use of multiple vibrators, however, has obscured optimal results with this approach. The identification of the information received by the cutaneous receptors appears to be elusive.

(4) Finally, it is viewed by this writer that considerable basic information is needed on tactile reception of the speech code before a clear potential for tactile sensory communication can be assessed. The purpose of the present study was to provide a "new beginning" in this direction.

# CHAPTER III

## SUBJECTS, EQUIPMENT, MATERIALS AND PROCEDURES

Six subjects were presented seriatem three experimental programs. The first program involved determination of intensity for detection threshold of English phonemes, the fundamental speech sounds. The second program was concerned with a description of the distinctive features of each of the phonemes. Subjects selected descriptive adjectives from a closed response set. The final experiment involved paired comparisons with a same-different response to determine if additional discriminations beyond distinctive feature descriptions are possible.

A pilot study was undertaken to resolve the following questions: (1) Can a tactile detection threshold be determined for each of the English phonemes? (2) What method of contactor attachment can provide optimal stability of threshold scores? (3) What bipolar adjective pairs can describe the distinctive features upon which tactile discrimination is based? (4) Do subjects become fatigued and thus significantly reduce their vigilance capacity during or after one hour of tactile stimulation? The results of the pilot experiment are incorporated under the appropriate sections of this Chapter and Chapter IV.

## Subjects

The six subjects, three males and three females, were professional persons trained in the area of audiology and speech pathology. The age range was 24 to 30 years. None of the subjects had clinically significant hearing losses as determined by recently completed pure tone threshold measures. None were known to have pathological conditions of the skin nor central nervous system.

The six subjects were initially introduced to the tactile discrimination task during the pilot study sessions. Specifically, each subject was exposed to two hours of tactile reception of spoken English phonemes. The first hour involved a seriatem program of randomly ordered phonemes recorded on magnetic tape and played through the tactile stimulus transmission system at an arbitrarily chosen intensity level of 30 dB, (re: 5 volts). The second hour, at least one day and not more than three days later, was devoted to describing the distinctive features for each of the phonemes. The exact procedures for determining detection thresholds and describing the distinctive features were the same for both the pilot study and the major investigation.

## Equipment

The following list constitutes the major instrumentation employed for this study:

Tape Recorder I (Ampex AG 350-2)
Tape Recorder II (Ampex AG 500)
Tape Recorder III (Ampex 601)
Tape Recorder IV (Magnecord 1022)
Tape Recorder V (Viking 433)
Microphone (Electrovoice 654)
Level Recorder (Bruel and Kjaer 2305)
Audio Oscillator (Central Scientific Company)
Commercial Test Room (Industrial Acoustic Company, Inc., single walled booth, series 400)
Commercial Test Room (Industrial Acoustic Company, Inc., double wall room, Model 10-1052)
Magnetic recording tapes (type 201, Scotch Brand)
Audiometer (Maico MA-24) with Electrovoice SP-12 speaker
Tactile stimulus transmission system with piezoelectric ceramic Bimorph (Clevite Corporation)
Sound Spectrograph Model PV10A (Voiceprint Laboratory)

## Materials

Magnetic tape programs of recorded English phonemes comprised the stimulus materials for the three experiments of this study. The fundamental English phonemes as described by Fletcher[1] were the basic units for all

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[1] Harvey Fletcher, "Acoustical Speech Powers," Chapter IV in Speech and Hearing in Communication, (Princeton, New Jersey: D. Van Nostrand Company, Inc., 1953), pp. 68-88.

stimulus events. As a result of the pilot study, two phonemes, /s/ and /θ/ were excluded. Apparently these speech sounds possess upper frequency composition which prohibits detection by the human sensory receptors of the skin under the current test conditions. This limitation was discussed in the previous chapter. The 36 phonemes used in the experiments were: /o/, /u/, /ɔ/, /a/, /e /, /i/, /u/, /·/, /æ/, /ɛ/, /I/, /aɪ/, /au/, /ɔɪ/, /w/, /j/, /h/, /l/, /ɝ/, /m/, /n/, /ŋ/, /v/, /z/, /dʒ/, /tʃ/, /f/, /d /, /t /, /ð/, /b/, /ʒ/, /ʃ/, /g/, /p/, and /k/.

Three programs of taped recordings were made. The 36 phonemes were recorded in a randomly ordered sequence making a master tape, tape 1. This program, with a single presentation of each phoneme, was used for training of the subjects and, in addition, served as a source for other programs.

Tape 2 contained eight consecutive repetitions of each phoneme, a total of 288 stimulus events. Each repetition was a replication of the original, single utterance from the master tape. This program was designed to provide the stimuli for determining the detection thresholds and distinctive feature descriptions.

Tape 3 contained 150 phoneme pairs. The selected pairings for "same-different" comparison included: (1) all phonemes previously described by identical descriptive adjectives, (2) a subset of phonemes described by different descriptive adjectives.

## Preparation of Materials

The master tape was recorded in the Speech Science Laboratory at Michigan State University. Recording was done by a male speaker with a General American dialect. The stimulus material was recorded via an Ampex AG 350 tape recorder employing an Electrovoice 654 microphone in a single walled sound treated booth (See Appendix 1 for frequency response data for all recording equipment). The phonemes were uttered as naturally as possible to attain proper stress, duration and relative speech power. Guides for this recording procedure were provided by Black[1], [2] and Fletcher.[3]

This preliminary tape was then played through the speech circuit of the Maico MA-24 audiometer for critical review by two speech pathologists. The listeners, seated in an adjoining IAC (Model 10-1052) sound treated room,

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[1] John W. Black, "Natural Frequency, Duration, and Intensity of Vowels in Reading," <u>Journal of Speech and Hearing Disorders</u>, 14 (1949), pp. 216-221.

[2] John W. Black, "Accompaniments of Word Intelligibility," <u>Journal of Speech and Hearing Disorders</u>, 17:4 (1952), pp. 409-418.

[3] Fletcher, "Acoustical Speech Powers,' pp. 68-88.

phonetically transcribed the stimuli they heard in the sound field. The tape was replayed to elicit their comments as to the naturalness of the utterances. The preliminary tape was then edited to eliminate errors. The Sound Spectrograph PV10A was employed to obtain spectograms for each of the taped phonemes. Analysis of the spectograms showed that no corrections were necessary by Black's data for phoneme durations (see Appendix 2). The preliminary tape was then dubbed onto another tape utilizing the Magnecord 1022 in conjunction with the Ampex AG 350.

A final step in the preparation of the master tape was an adjustment of the relative intensities of the phonemes to meet the relative speech power dimensions as specified by Fletcher.[1] The strongest speech sound /ɔ/, for example, is specified as 28 dB stronger than the weakest sound, /θ/. A level recorder (Bruel and Kjaer 2305) was used to measure the relative intensities of the phonemes on the preliminary recording. In order to determine needed adjustments the peak values were equated to the desired relative intensities (± 2 dB). The corrected levels were achieved by adjusting the output of the Magnecord 1022. The phonemes were re-recorded on the Ampex AG 350 at the appropriate levels. The resulting

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[1] *Ibid.*

master tape was replayed through the level recorder for a final check of relative intensities. Appendix 2 describes the relative intensity differences of the 36 recorded phonemes.

In that the /ɔ/ sound was assigned the highest intensity value, this value was used to determine the intensity needed for the calibration tone. One minute of a 1000 Hz sinusoidal tone was recorded at the beginning of the tape at this level.

The master tape provided the stimulus materials for two additional tapes. The second tape was dubbed from the master by the use of an Ampex AG 500 in conjunction with an Ampex 601 recorder. This taped program had the same random ordering of phonemes as the original recording. Each phoneme, however, was dubbed on tape 2 eight consecutive times with an inter-stimulus interval of three seconds. Six seconds of leader tape was spliced on the tape between each set of eight repetitions.

Tape 3 provided 150 pairs of phonemes for the paired-comparisons task in Experiment III. The phonemes were dubbed from the master tape with the same equipment used in preparation of tape 2.

Tape segments contained 300 individual stimulus events for the 150 pairs of phonemes. The order of the phonemes within a pair was dictated by chance and the entire list of pairs was ordered randomly. The tape segments were spliced together with one second of leader tape between each stimulus event of a pair and three seconds of leader tape between pairs.

The Tactile Stimulus Transmission System. A major requirement for this study was the development of a tactile stimulus transmission system. Research reports from the Princeton University Cutaneous Research Laboratory proved valuable in developing a suitable system.[1] These reports, along with personal communication[2] with the major investigators at the Princeton University Laboratory, provided convincing evidence in favor of the piezoelectric ceramic Bimorph developed and made commercially available at the Clevite Corporation of Bedford, Ohio. The Bimorph has the following attributes: simplicity of design, broad frequency response characteristics, almost instantaneous "on-time" of transmitted signals, and excellent manageability for coupling with the skin (see Appendix 3).

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[1] Frank A. Geldard and Carl E. Sherrick, "Princeton Cutaneous Research Project - Report No. 13," (unpublished document, Princeton University Cutaneous Research Laboratory, Princeton University, March 1, 1969).

[2] Geldard, Telephone Communication, December 30, 1969.

The Bimorph vibrator employed in this study (PZT-5B) measures 1 1/4 inches in length, 1/8 of an inch in width, and 0.021 of an inch in thickness. The device uses flexure responsive piezoelectric elements as transducers for mechanical output as a function of electrical input. A Bimorph is a 0.002 inch thick brass plate with a ceramic material bonded to the top and bottom surfaces. Figure 1 illustrates this arrangement.

The framework for housing the Bimorph involved a cantilever mounting, also illustrated in Figure 1.

In order to respond flexurally to the input signals, the Bimorph must have its two active ceramic plates oppositely polarized. This produces oppositely direct transverse strains which result in bending or deflection of the free end. Motion sensitivity is derived in terms of deflection per unit of applied voltage. The maximum limit for applied voltage is 260 volts. Any excess over this amount may cause destruction of the vibrator.

The cantilever mounting for the Bimorph also served as the means of electrical contact. Specifically, this was achieved by connections to the two brass plates forming the clamp to hold the top and bottom surfaces of the vibrator.

Figure 1. Cantilever Mounted Bimorph

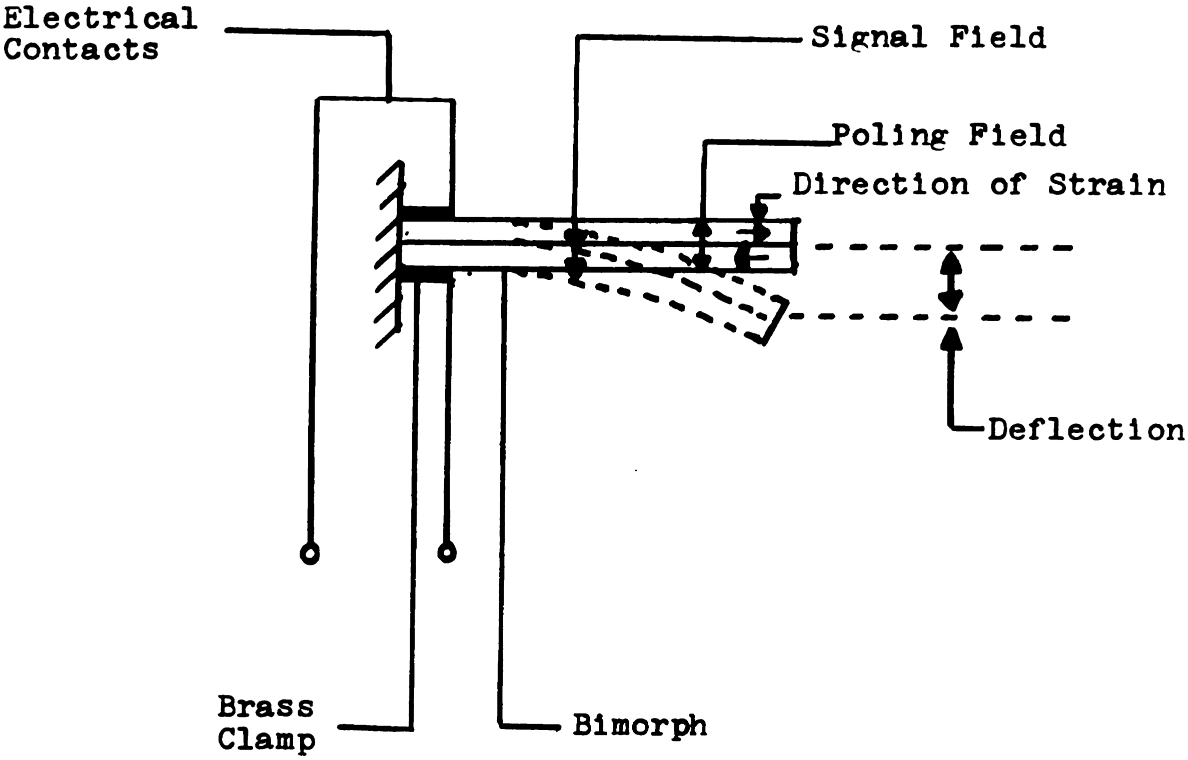
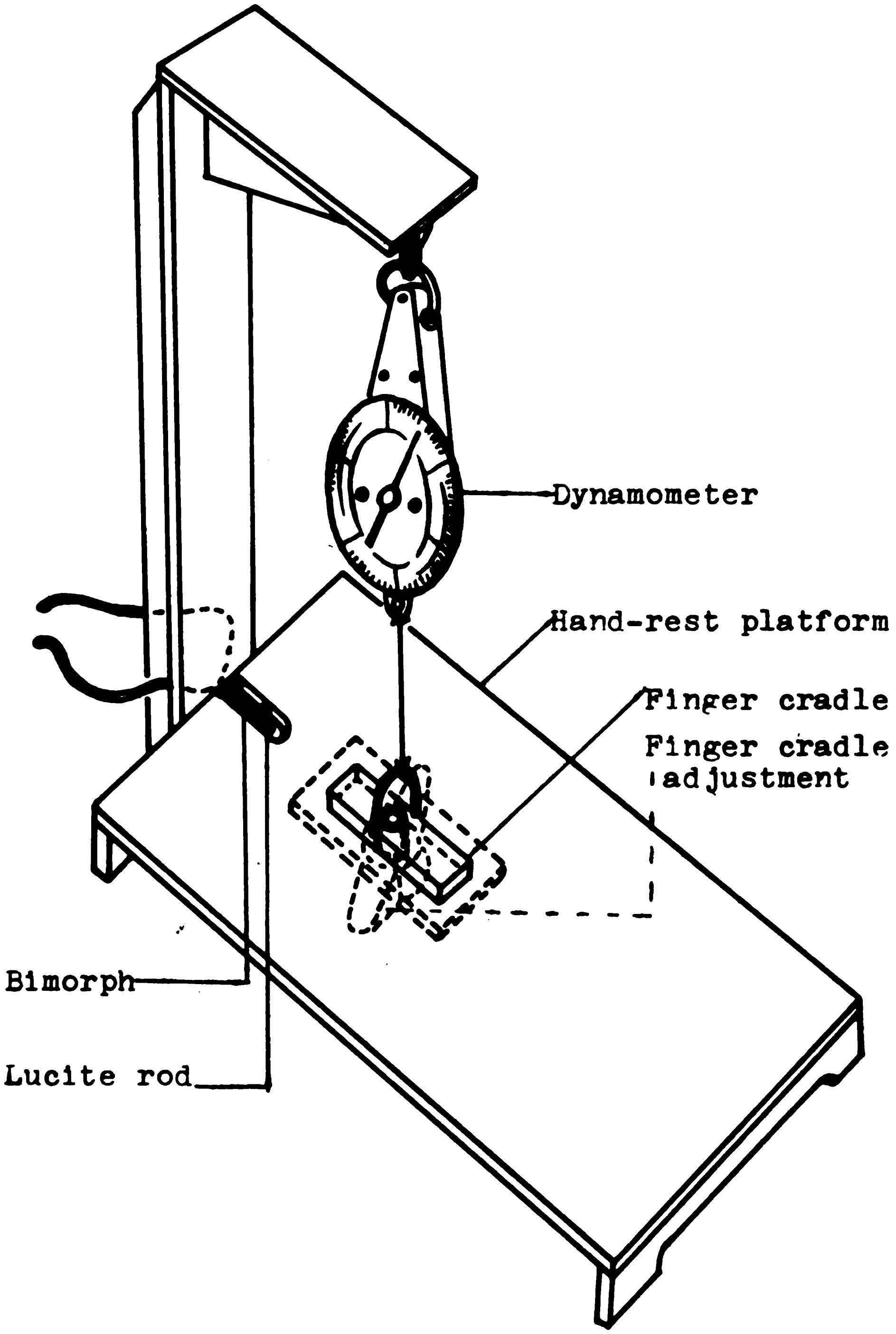
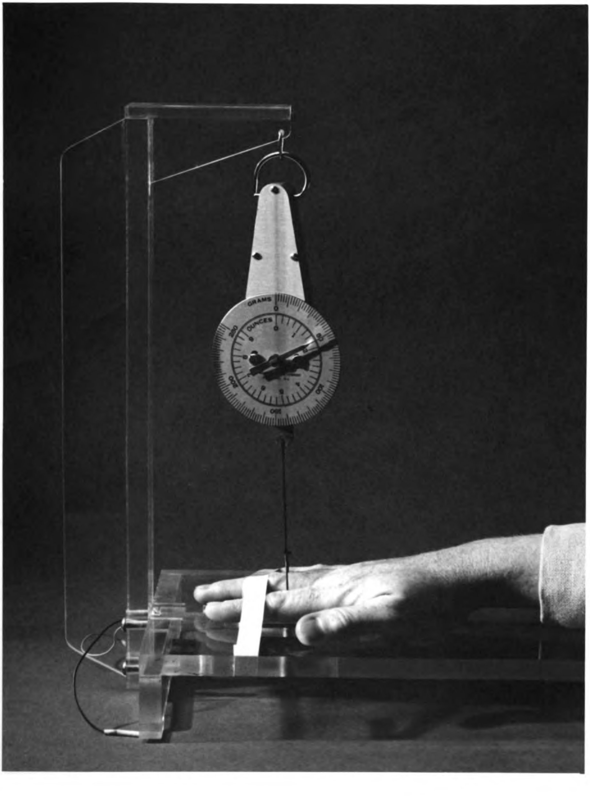


Figure 2. Apparatus for housing Bimorph (PZT-5H)





GRAMS
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150
100

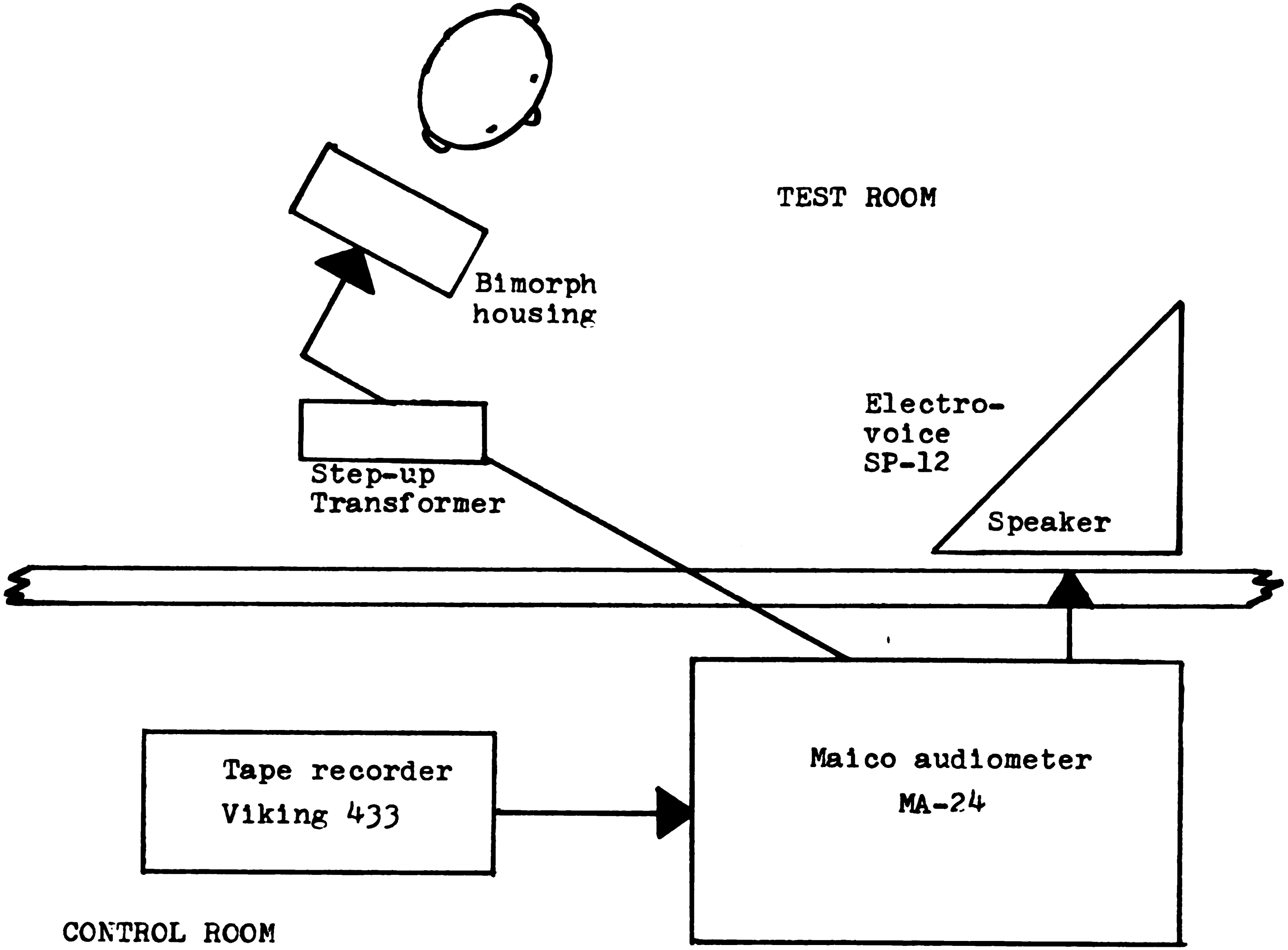

Figure 3. A schematic diagram of stimulus transmission system, test room and adjoining control room.

The skin-contactor coupler was a Lucite rod, 1/8 inch in diameter. The contactor was secured to the outer-most free end of the Bimorph by a small (2-48) flat head screw. The screw was attached with epoxy glue. This arrangement allows for fastening contactors of various sizes. The desired length of the contactor was dictated by the design of the plexi-glass hand-rest platform in relation to the adjustable finger cradle of the apparatus. Figure 2 illustrates this arrangement. The construction provided an 1/8 inch extension of the Lucite rod above the handrest platform. The adjustable finger cradle could be lowered to a position whereby it was exactly parallel to the hand-rest platform. This allowed variation in adjustment of the pressure against the contactor by the fingertip up to 40 grams. The site on the integument for coupling was the inner-most concentric fingerprint line of the third finger of the right hand, the inner-most papillary ridge.

According to the Clevite Corporation, the mass loading of the Bimorph by the Lucite contactor rod presents no significant deterent to the performance of the vibrator. The loading by the fingertip, however, does influence an interaction between deflection rate and voltage. Resonant frequency is not affected (see

Appendix 3). A design chart was provided by the manufacturer which was used to determine the specifications for applied voltage, pressure at the contactor, and for the length and width of the Bimorph[1] (see Appendix 3).

An 11 1/2 inch high plexi-glass post was attached to the vibrator end of the hand-rest platform. A 3 1/2 inch long plexi-glass support plate was secured to the top of the post and extended over the finger cradle. A dynamometer scaled in grams, was suspended from the support plate and coupled to the finger cradle by a 2 1/2 inch string. Thus, as the finger cradle is lowered the relative pressure can be read directly from the dynamometer. Figure 2 depicts this construction.

A Viking 433 tape recorder in conjunction with a Maico MA-24 audiometer completed the tactile stimulus transmission system. All taped programs were played through this system at their recording speed of 7 1/2 inches per second. This recorder model has the advantage of an output level meter which can be adjusted for gain control (see Appendix 4).[2]

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[1] C. P. Germano, "Some Design Considerations in the use of Bimorphs as Transducers," Technical Paper TP-237 (Bedford, Ohio: Clevite Corporation), March 5, 1969, 15 pp.

[2] Appendix 4 provides frequency response data for the components of the Tactile Stimulus Transmission System.

The stimulus materials were amplified and attenuated by the Maico audiometer. The stimuli were transmitted through the speech circuit of channel one which allows one dB adjustments of the signal intensity. This equipment has a range of 120 deciBels. Because of the nature of the test materials, limited applied voltage tolerance of the Bimorph, and the limitations of the sensory receptors of the skin, a useful range of only 45 dB was realized.

In summary, the major instrumentation comprising the tactile stimulus transmission system consists of a Viking 433 tape recorder-player, a Maico MA-24 audiometer, the Bimorph, and the apparatus housing the vibrator.

Calibration. The equipment was calibrated prior to each of the three experiments. The Maico MA-24 audiometer was calibrated to the transducer (Bimorph) by taking voltage measurements across the electrical terminals to the Bimorph. The measurements of the broad band, white masking noise emanating from the Electrovoice SP-12 loudspeaker were made with the experimenter observing the sound level meter readings from the test room. Appendices 4 and 8 describe the procedures and metrics of equipment calibration. No systematic differences were found during the process of this study in the calibrations of the stimulus transmission system.

## Procedure

All experimental sessions were conducted in an IAC double-walled room. For each experiment each subject was comfortably seated beside a table with his right arm resting on a 1/4 inch foam rubber pad. The right hand, palm down, was placed on the hand-rest platform of the apparatus for tactile stimulation. The middle finger was placed in the finger cradle with the finger tip extended over the Lucite rod contactor. Care was taken to couple the fingertip by contact at the innermost concentric fingerprint line. The finger and hand were secured for position by a single strap of adhesive tape. The finger cradle was elevated to remove coupling with the contactor. The cradle was then lowered to a point where the subject could just begin to detect contact. A reading was made on the dynamometer and the cradle was lowered an additional 15 grams of applied pressure. This amount of applied pressure, ± 5 grams, is recommended as optimal when employing a Bimorph in a cantilever mounting.[1] There is, however, no evidence in the literature as to the effects of varying amounts of applied pressure when employing cantilever mounted vibrators. In this procedure, pressures

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[1] Telephone conversation by author with C. E. Sherrick, January 5, 1970, Princeton Cutaneous Research Laboratory.

exceeding this amount can result in decreased sensitivity.

To assure against any perceived auditory signals emanating from the transducer, all experiments were completed with 80 dB SPL of broad band white noise projected into the sound field from the speaker in the test room.[1] The noise was generated through channel two of the Maico audiometer. A sound pressure level analysis of all the speech sounds emanating from the Bimorph showed a maximum level of 54 dB SPL for the /ɔ/ sound.

Experiment I. The purpose of the first experiment was to determine the various intensities required to elicit detection thresholds for the 36 phonemes.

Before each test session, the calibration tone was used to adjust the output gain of the Viking tape recorder to the level of zero on the VU meter. A simultaneous adjustment to zero on the Maico Audiometer VU meter was also made. The individual test sessions were initiated with a short practice session to re-familiarize the subjects with the nature of the tactile sensations to be received. The stimuli were presented at a 40 dB

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[1] Ibid. Eighty dB SPL is the standard level used in all experiments at the Princeton Laboratory.

(re: 1.6 volts) intensity level.[1] Although no overt response was required, the subjects were asked to concentrate on the tactile sensations received.

Following the practice session the second programmed tape was employed to elicit the detection thresholds. The psychophysical method of limits, defined earlier, was used. For all subjects, with each phoneme, there were four ascending series and four descending series. In each case the ascending series was first, followed by a descending series, then an ascending series, and so on. For the first ascending series an alerting signal, a phoneme, was presented at the maximum intensity limits of the equipment. This was followed by a stimulus of very low magnitude which was progressively increased until it was detected. The intensity at this point was recorded as the threshold for the series. The signal was further augmented by 1 dB steps and responses noted for three additional trials. At this final level the process was reversed and the descending series began. The signal was reduced in magnitude by 1 dB steps until the stimulus was no longer detected. The intensity level at which the signal was last reported present in the descending series was recorded as the threshold for the

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[1] Specified for zero dB, representing the lowest threshold for a subject during the pilot study.

series. The signal was further attenuated in 1 dB steps for three additional trials. At this final level the next ascending series began. This procedure was repeated for the remaining series. The average score for the eight series served as the threshold for a given phoneme.

The subject response was pressing a signal button each time the stimulus was detected. The experimenter recorded the thresholds for each of the subjects on a form as presented in Appendix 5.

The order of presentation of the phonemes was determined randomly. Three of the subjects were presented the first 18 of the 36 phonemes first, and three received the last 18 phonemes first.

The following instructions were read to each subject prior to the experiment:

> The purpose of this session is to determine what intensity is required in order for you to determine the presence of a tactile sensation. Each stimulus event represents an English phoneme. In other words, we are interested in absolute thresholds of detection. Please respond on every occasion that you detect a vibration on your finger tip. Respond by briefly pressing this button. Most of the stimuli will be presented around your threshold; therefore, this task will require constant concentration on your part. Several presentations will be given for each phoneme. There will be both ascending and descending series. The first presentation of a phoneme, before all the series for that phoneme, will be rather strong. This will alert you to the nature of the sensation for that particular phoneme. Between phoneme series the masking noise will be substantially reduced. This will indicate

> to you that we have completed the threshold series for a phoneme. When the masking noise is re-initiated the next phoneme presentations will begin. Remember that the first stimulus will be strong. In that this experiment will take about two hours, you will be given a ten minute rest after one-half the list of phonemes is completed. Are there any questions?

<u>Experiment 2</u>. Approximately one week later each subject returned to participate in the second experiment. Calibration of the equipment, positioning of the subject, and the practice period were as described in Experiment 1.

The purpose of this task was to determine how the subjects describe the distinctive features for each of the phonemes. The results of the pilot study indicated only three practical dimensions of description: strong versus weak, short versus long, changing pattern versus nonchanging pattern. Tape 2 composed of the eight consecutive repetitions of each phoneme, served as the program.

The instructions read to the subjects describe the specific procedures involved. They were as follows:

> The task for this session is to evaluate all the phonemes with respect to their tactile patterns that you perceive. In other words, we are interested in the "distinctive features" of each phoneme. Each phoneme will be repeated in succession six times. After every other sensation you will be asked to make a judgment. Stated in another way, you will feel the sensation twice and make a judgment, twice more and make a second judgment, and so on. Here are the judgments you will make: strong or moderate or weak or very weak, long or short, changing pattern or nonchanging pattern. Now, in summary, you will receive the sensation transmitted by each phoneme six times. Two

> sensations will be allowed before each judgment. In each case you indicate to me your choice by saying the adjective aloud. Please follow the order of the wall charts. For each phoneme there will be three judgments. After you have given me your responses for each phoneme, there will be a reduction in the masking noise as in the previous experiment. The noise will be re-initiated to alert you to the fact the next series is beginning. Are there any questions?

The adjectives for subject description of the distinctive features were printed on three 5 x 7 1/2 inch index cards. The three cards were mounted on the wall of the test chamber in the following order: (1) strong, moderate, weak, very weak; (2) long, short; and (3) changing pattern, nonchanging pattern. The subjects' responses were recorded on a form which is presented in Appendix 6. All stimuli were presented at an intensity level of 40 dB (re: 1.6 volts).[1]

Experiment 3. Within one week following Experiment 2, Experiment 3 was completed. The purpose of the final experiment was to determine if finer discriminations beyond the distinctive feature descriptions were possible.

Paired comparisons with a response set of same-different were employed. The program of tape 3 provided the phoneme pairs. Criteria were established for determining the comparisons desired. Pairings were made for:

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[1] Specified for zero dB, from threshold data (Experiment 1) representing the lowest threshold for a subject for a given phoneme (subject 4, phoneme /u/).

(1) all phonemes with identical distinctive features on all dimensions,

(2) randomly selected phonemes differing on one or more dimensions,

(3) all phonemes which were not described with the same distinctive features by at least five of the six subjects.

With these criteria and the results achieved from Experiment 2, 150 paired comparisons were presented for subject responses.[1]

The purpose of randomly choosing a phoneme to represent each of the eight groups of identically described phonemes was to check the validity of the subject judgments on the distinctive feature task. The logic was that if the subjects described the phonemes as being distinctively different on the previous experimental tasks, paired stimuli with each member of the pair differing on at least one dimension should consistently elicit a "different" response for this experiment.

Thus as a result of Experiment 2, pairs were presented for a same-different response when phonemes were previously described identically, when phonemes

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[1] The eight possible groups comprising phonemes with identical features are: Group 1 (strong, long, changing), Group 2 (strong, long, nonchanging), Group 3 (strong, short, changing), Group 4 (strong, short, nonchanging), Group 5 (weak, long, changing), Group 6 (weak, long, nonchanging), Group 7 (weak, short, changing), and Group 8 (weak, short, nonchanging).

differed on one or more dimensions, and when subject agreement was less than five out of six.

Prior to the experiment calibration of the equipment, positioning of the subjects, and the practice sessions were completed as described in Experiment 1. In addition, a reliability check for detection thresholds was performed on each subject. The procedure for this was the same as in experiment 1. Only ten phoneme thresholds were obtained, however. The specific phonemes for a given subject's retest were pre-experimentally determined to represent a reliability check on each of the 36 phonemes as well as a reliability measure for subject performance.

Upon completion of the tasks described above, the following instructions were read:

> The purpose of this last task is to determine how well you can discriminate between pairs of successive sensations. You will receive a stimulus, a one second interval of no stimulus, and then the second stimulus of the pair. Please say aloud: "same" if you judge the sensations as identical; or "different" if you judge the sensations as not the same. Between pairs of sensations there will be a three second interval for your response.

All stimuli were presented at an intensity level of 40 dB (re: 1.6 volts). Five practice pairs were presented before scoring of the subject responses was initiated. Scoring was completed on a subject response sheet as presented in Appendix 7.

After a ten minute rest period, the entire taped program for Experiment 3 was presented again to allow an evaluation of the subjects' reliability of judgments.

# CHAPTER IV

# RESULTS AND DISCUSSION

**This chapter presents basic data and discussion** relative to the three experimental questions of this study:

1. What is the intensity level required for vibrotactile absolute thresholds for each of the English phonemes?
2. How do subjects describe the "distinctive features" for each of the English phonemes when they are required to make judgments from a closed response set?
3. Are further discriminations possible by using paired comparison judgments of phonemes categorized with identical tactile distinctive features?

## Experiment 1

Initially, attention was focused on determining if detection thresholds could be obtained for all the phonemes. Pilot investigation indicated that thresholds were not possible for the /s/ and /θ/ sounds. Aside from the limitations of instrumentation, two additional observations might account for the difficulty. First, both sounds are comprised of extremely high frequency composition (4000-6000 Hz). According to Fletcher,[1] all

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[1] Fletcher, "Acoustical Speech Powers," p. 87.

other speech sounds have frequency composition below this range. Secondly, the /θ/ has the lowest relative speech power of all the fundamental speech sounds, while the /s/ sound is ranked 27th, well down in the distribution, from the most powerful /ɔ/ sound (see Appendix 2).

The /s/ and /θ/ phonemes are not, therefore, shown in the detection threshold data presented in Table 1. The mean threshold scores and standard deviations for the six subjects are given for the remaining 36 phonemes. The range in deciBels (re: 1.6 volts)[1] is 4 dB for the /u/ sound to 44 dB for the /f/ sound. The standard deviations indicate the considerable consistency among subjects' responses. The range of standard deviations is from 0.9 dB for the /f/ and /ʃ/ sounds to 2.9 for the /n/ sound.

Each threshold determination was based on four ascending and four descending series of stimulus presentations. Comparison was made between the mean ascending threshold intensity and the mean descending threshold intensity averaged over all subjects and all phonemes in each case. The overall mean was 16.0 dB (re: 1.6 volts)

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[1] Specified for zero dB, representing the lowest threshold for a subject for a given phoneme (subject 4, phoneme /u/).

Table 1. Group means and standard deviations of six subjects for 36 English phonemes ranked according to detectability.

| Phoneme | Detection Threshold in dB (re: 1.6 volts) | Standard Deviation |
|---|---|---|
| u | 3.7 | 2.7 |
| o | 5.1 | 2.0 |
| ɪ | 5.3 | 1.9 |
| ɛ | 5.7 | 2.0 |
| ŋ | 5.7 | 2.2 |
| ʊ | 6.4 | 1.9 |
| ʌ | 7.0 | 2.2 |
| e | 7.2 | 2.6 |
| i | 7.3 | 2.3 |
| l | 9.1 | 2.7 |
| w | 9.5 | 1.9 |
| æu | 9.6 | 1.6 |
| ɔ | 9.6 | 2.2 |
| ɝ | 10.1 | 1.7 |
| aɪ | 10.3 | 1.4 |
| ɔɪ | 10.4 | 2.1 |
| ɑ | 11.8 | 1.5 |
| j | 12.2 | 1.5 |
| æ | 12.2 | 1.9 |
| v | 12.9 | 1.9 |
| p | 13.2 | 2.1 |
| m | 17.1 | 2.7 |
| n | 17.3 | 2.9 |
| k | 19.0 | 2.4 |
| g | 19.1 | 2.0 |
| tʃ | 19.8 | 2.0 |
| dʒ | 19.8 | 1.7 |
| d | 20.0 | 1.7 |
| b | 22.4 | 1.9 |
| t | 22.6 | 1.4 |
| ð | 22.7 | 2.6 |
| z | 23.2 | 1.7 |
| ʒ | 25.1 | 2.5 |
| h | 30.1 | 1.5 |
| ʃ | 43.3 | 0.9 |
| f | 44.3 | 0.9 |

for the ascending series and 14.5 dB for the descending series.

Figure 4 provides a graphic illustration of the rankings of the phonemes by detectability thresholds. Inspection of Table 1 and Figure 4 shows that all of the vowels fall into a compact range of eight dB requiring minimal energy for detection. The consonants, however, covered a range of 31 dB from 13 dB (re: 1.6 volts) for the /v/ sound to 44 dB for the /f/ sound.

If one considers the /w/, /j/, /ɝ/ and /l/ sounds as vowel glides,[1] Figure 4 shows that all the vowel sounds are clustered together, requiring less energy for detection than the consonants.

The high threshold energy required for the /h/, /ʃ/ and /f/, again, demonstrates the common effects of low speech power and high frequency composition. The effect on thresholds of phonemes with basically high frequency composition can be seen in Figure 5. The master tape of the single utterances of phonemes was submitted to spectrographic analysis and the derived lowest frequency energy concentrations were plotted on the abscissa. In the case of the /h/ sound, three weak equal levels of energy concentration were found.

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[1] Judson and Weaver, "Articulation," p. 154.

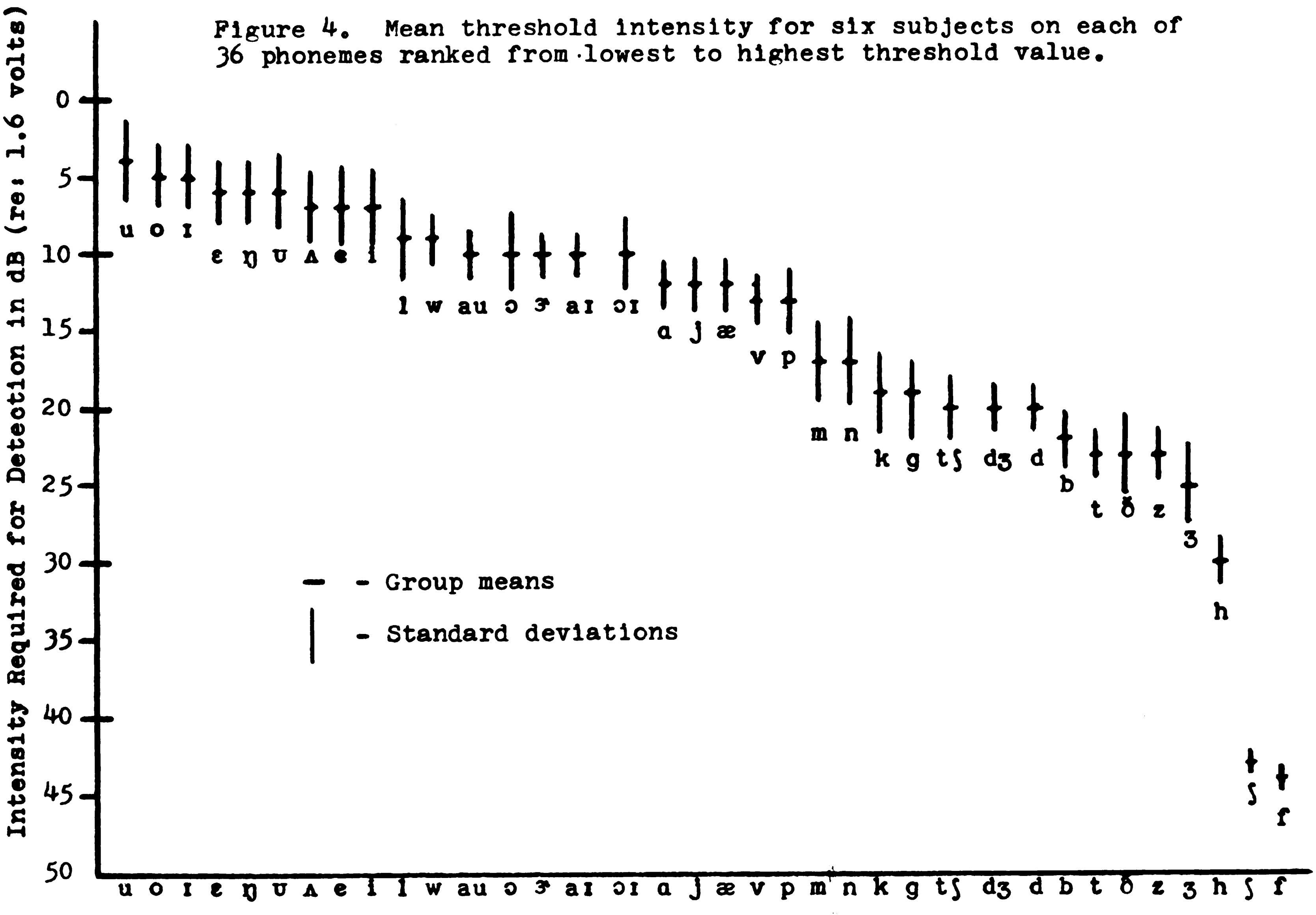
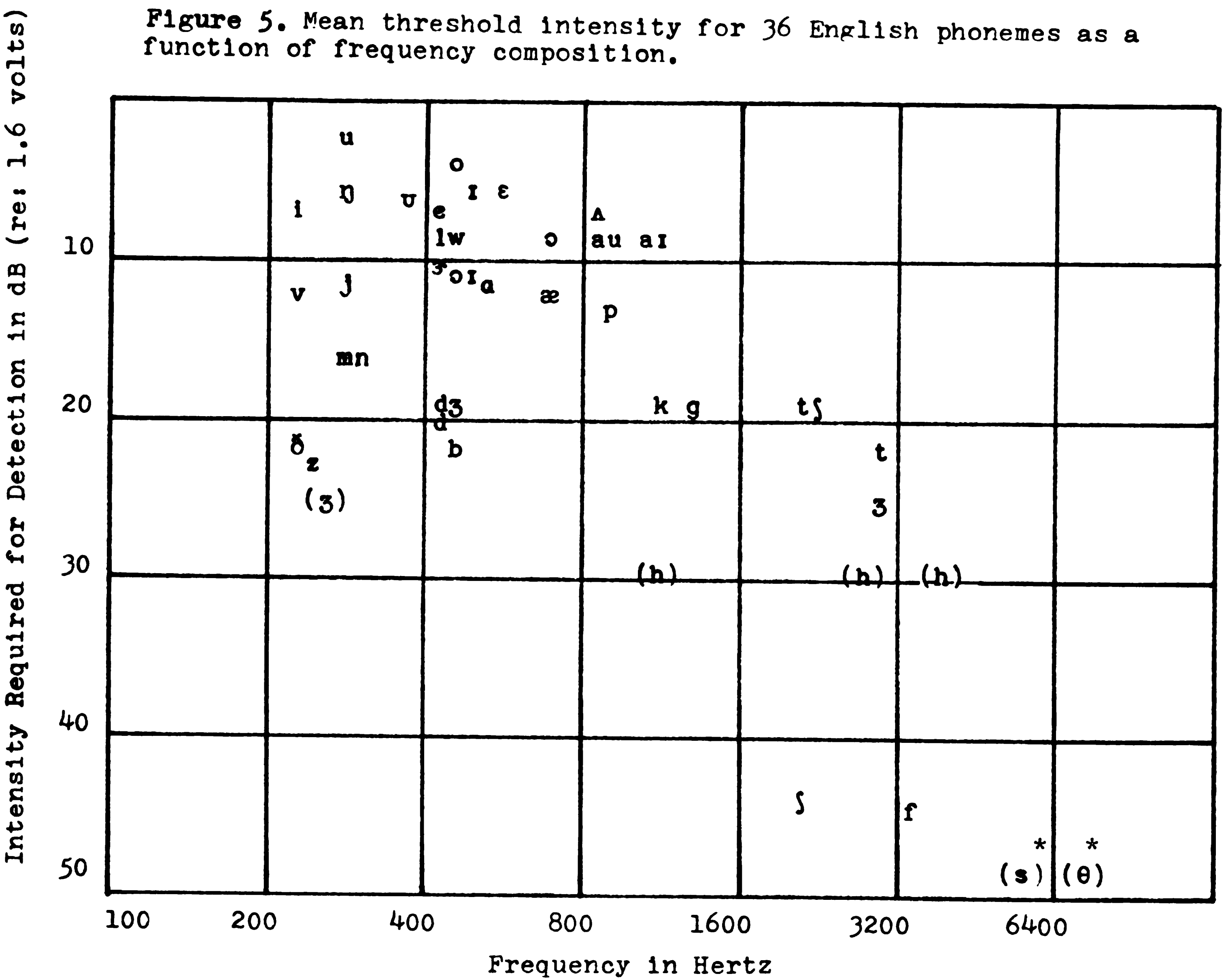


Figure 4. Mean threshold intensity for six subjects on each of 36 phonemes ranked from lowest to highest threshold value.

**Figure 5.** Mean threshold intensity for 36 English phonemes as a function of frequency composition.



*Detection thresholds not elicited, frequency values from Fletcher, p. 87.

Appendix 2 provides the metrics for frequency and duration transposed from the spectrograms for each phoneme. When one considers the further effects of relative speech power on the thresholds, the array of scores observed in Figure 4 is more fully explained. Phonemes with low speech power and only high frequency composition require more energy for tactile detection than phonemes with high speech power and low frequency composition.

Figures 6-11 show each subject's threshold performance compared to the group performance. The abscissa ranks the phonemes from low threshold values to high threshold values by the group mean scores for each phoneme. Individual deviation from group performance can be observed as very minimal. Regarding individual performance, Subject 4 gave relatively lower thresholds than the Group; Subject 6 tended to demonstrate relatively higher thresholds.

*Agreement Among Subjects' Threshold Scores*. The null hypothesis that there is no agreement among subjects for vibrotactile thresholds of detection for spoken phonemes, was tested by the nonparametric Coefficient of Concordance (Kendall's *W*). This procedure is applicable when a rank correlation is needed for more than two sets of

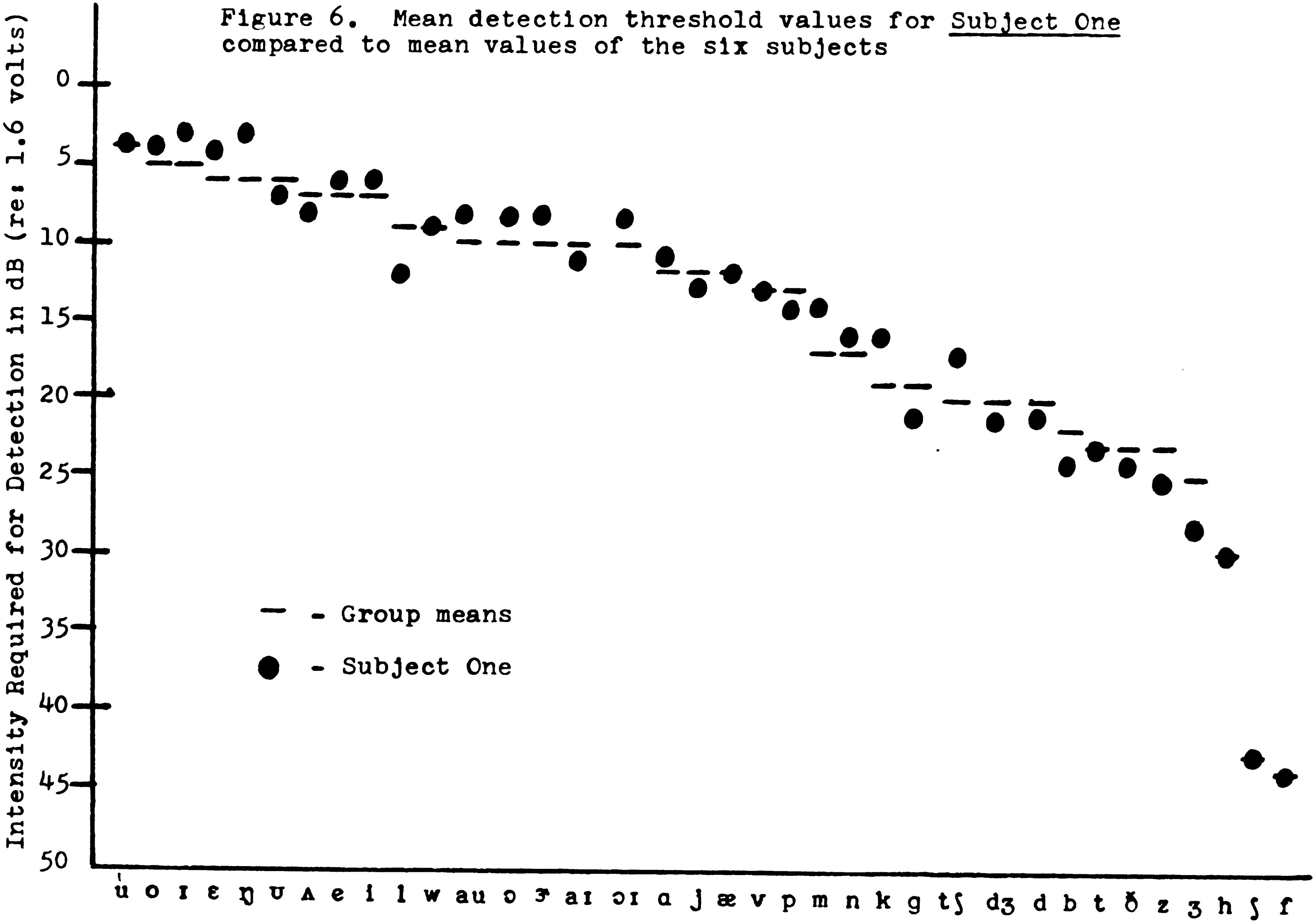
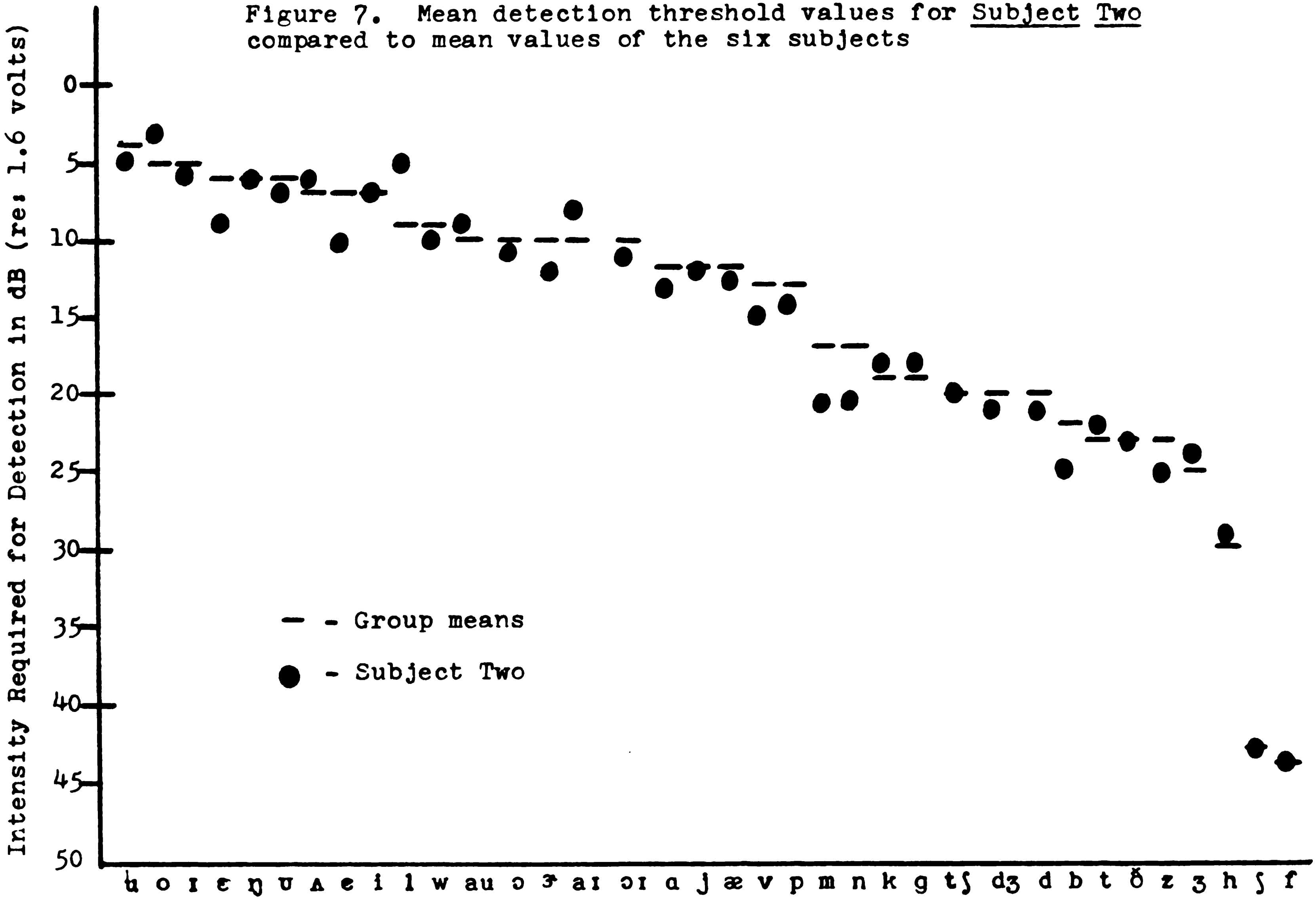


Figure 6. Mean detection threshold values for Subject One compared to mean values of the six subjects

Figure 7. Mean detection threshold values for <u>Subject</u> <u>Two</u> compared to mean values of the six subjects



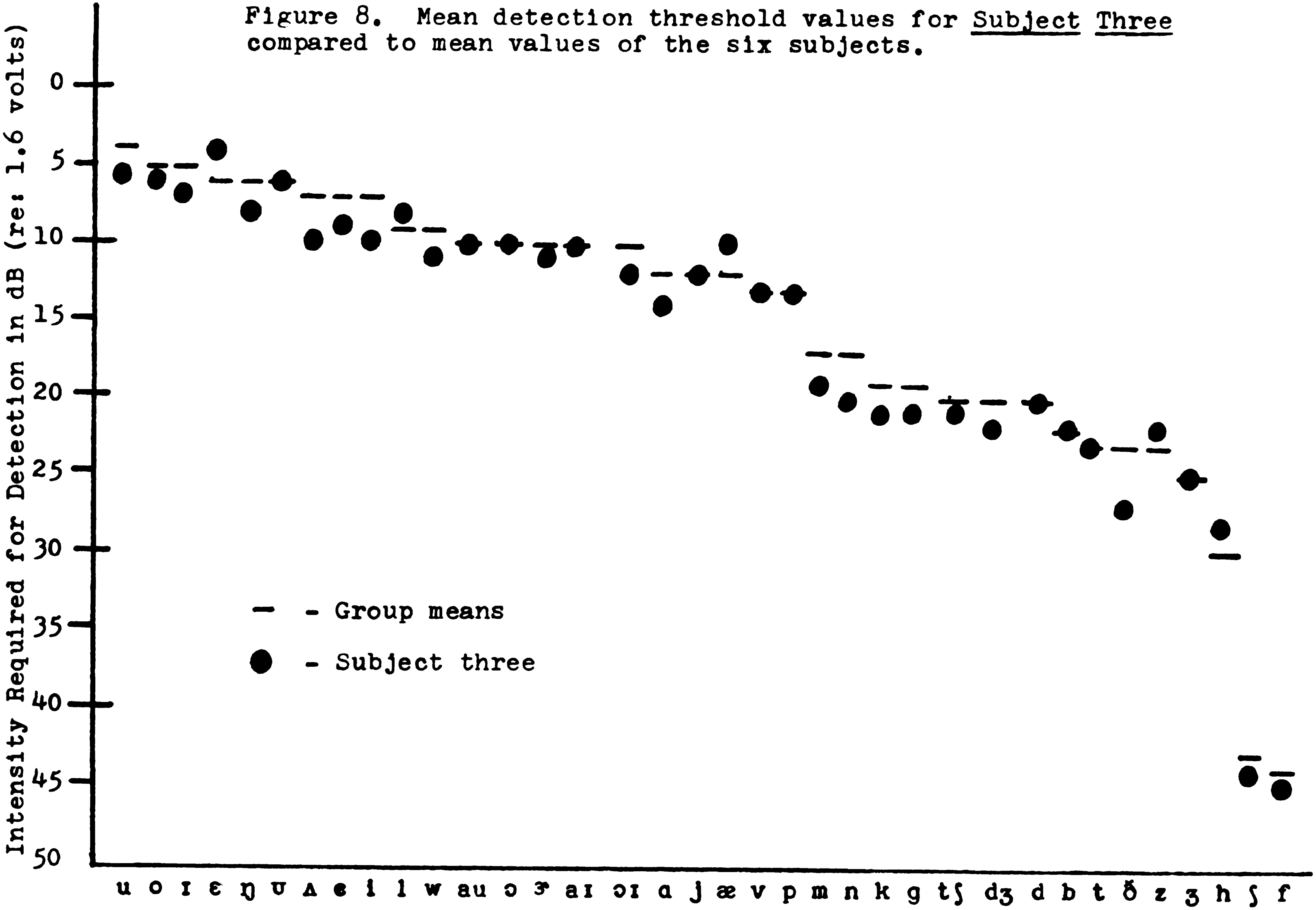
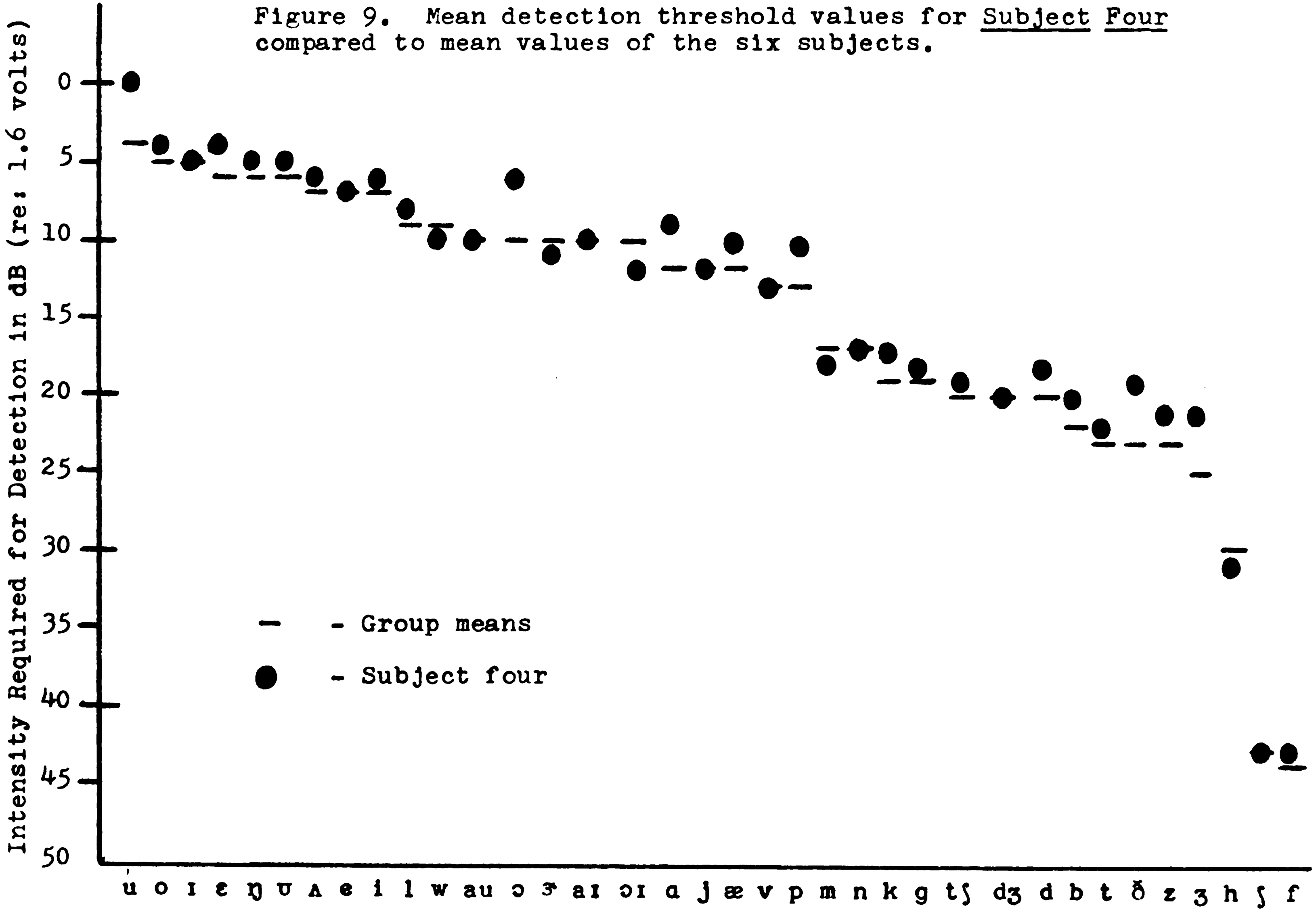


Figure 8. Mean detection threshold values for Subject Three compared to mean values of the six subjects.

Figure 9. Mean detection threshold values for <u>Subject Four</u> compared to mean values of the six subjects.



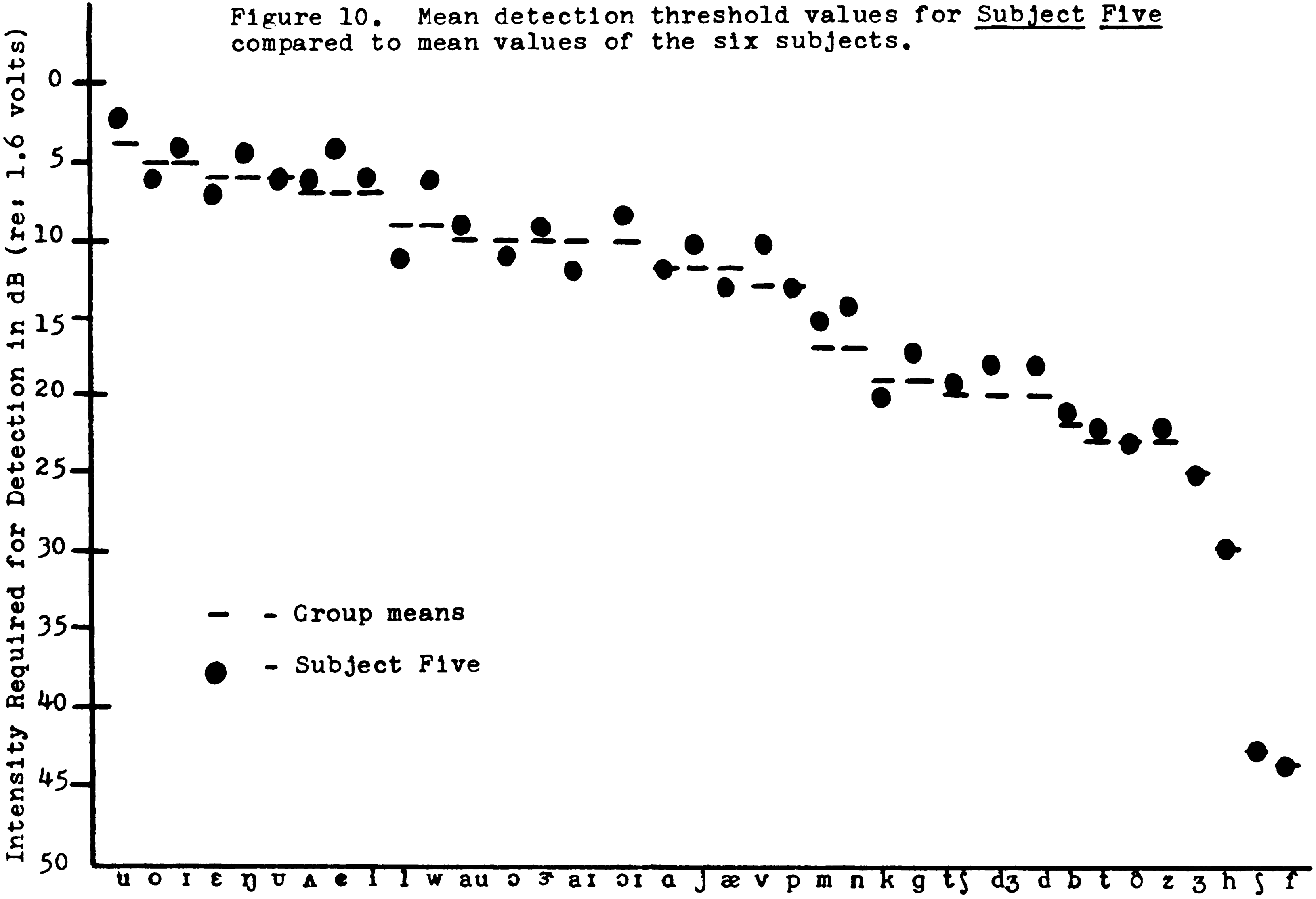


Figure 10. Mean detection threshold values for <u>Subject</u> <u>Five</u> compared to mean values of the six subjects.

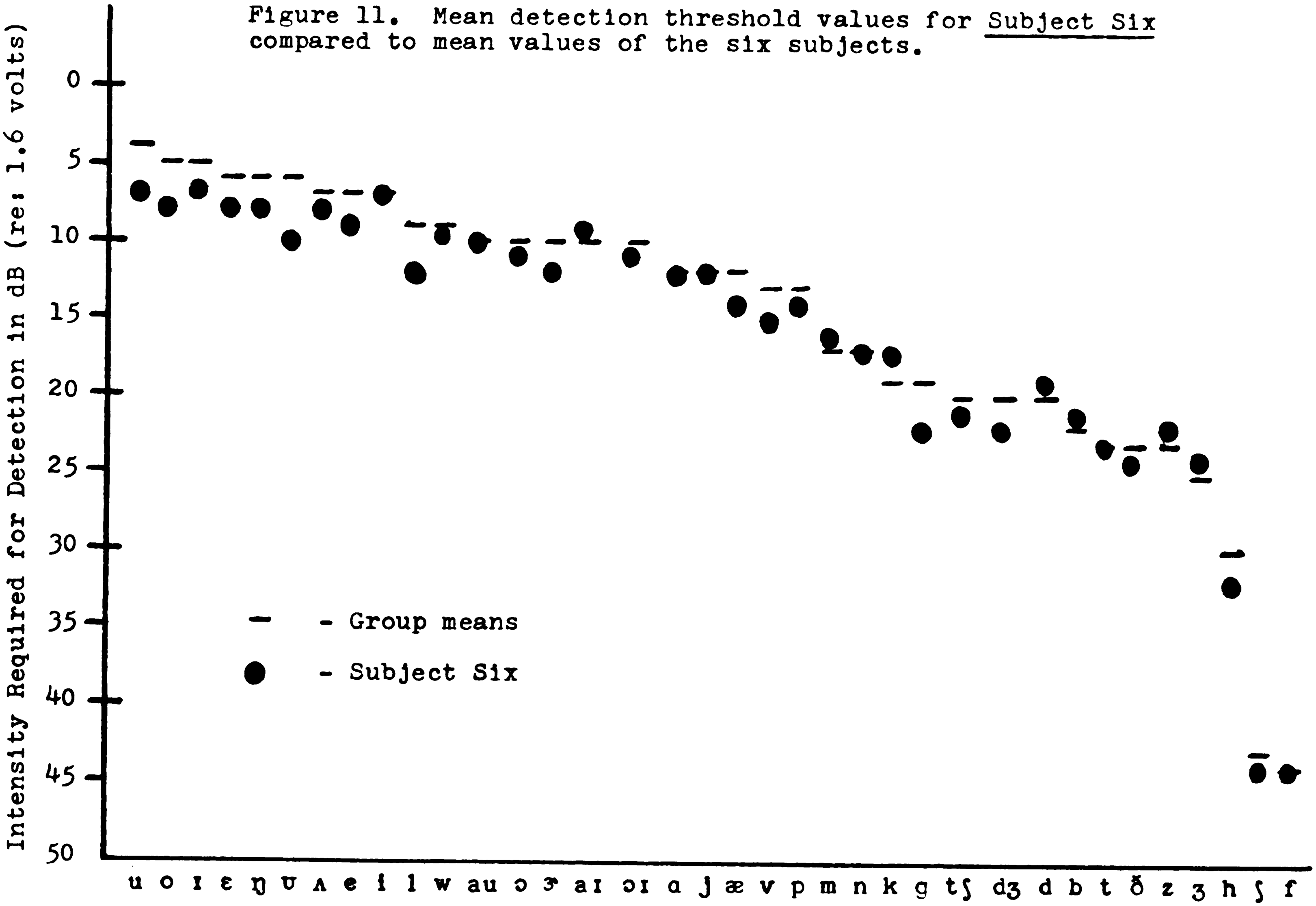


Figure 11. Mean detection threshold values for Subject Six compared to mean values of the six subjects.

ranks.[1, 2] For the six subjects and 36 variables (phonemes) a W of 0.95 was found.

The test of significance used the chi square approximation because the number of items ranked was large, N=36:[3]

$$\chi^2 = 199.5, \quad df = 35, \quad p \leq 0.001,$$

indicating extremely close agreement. Table 2 shows closer agreement was achieved for the consonant sounds than for the vowels. In fact, perfect agreement can be observed for the /h/, /ʃ/ and /f/ sounds by rankings of 34, 35 and 36 respectively.

Individual Subject Test-Retest Reliability. A Pearson Product Moment Correlation Coefficient was computed to evaluate the relationship between test and retest threshold responses for each of the six subjects. The results are presented in Table 3.

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[1] N. M. Downie and R. W. Heath, Basic Statistical Methods, (New York: Harper & Row, 1965), p. 209.

[2] The formula is: $W = \frac{12 \Sigma D^2}{m^2 (N) (N^2-1)}$;

where "D" equals the difference from the mean of the sum of the ranks, "m" equals the number of the subjects, and "N" equals the number of variables.

[3] S. Siegel, Nonparametric Statistics for the Behavioral Sciences, (New York: McGraw-Hill Book Company, Inc., 1956), p. 237.

Table 2. Rank orders of 36 English phonemes based on individual subject's threshold measures.

| | Phonemes | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subject | o | u | ɔ | ɑ | e | i | ʊ | ʌ | æ | ɛ | ɪ | aɪ | au | ɔɪ | w | j | h | l | ɝ | m | n | ŋ | v | z | ð | ʒ | f | ʃ | b | d | dʒ | g | p | t | tʃ | k |
| 1 | 4 | 3 | 12 | 16 | 7 | 6 | 8 | 11 | 17 | 5 | 1 | 15 | 9 | 10 | 14 | 20 | 34 | 18 | 13 | 21 | 23 | 2 | 19 | 32 | 30 | 33 | 36 | 35 | 31 | 28 | 26 | 27 | 22 | 29 | 25 | 24 |
| 2 | 1 | 3 | 14 | 18 | 12 | 8 | 2 | 6 | 19 | 9 | 7 | 10 | 11 | 15 | 13 | 16 | 34 | 4 | 17 | 25 | 27 | 5 | 21 | 32 | 30 | 33 | 36 | 35 | 31 | 28 | 26 | 22 | 20 | 29 | 24 | 23 |
| 3 | 3 | 2 | 11 | 21 | 8 | 13 | 4 | 10 | 14 | 1 | 5 | 12 | 9 | 17 | 16 | 18 | 34 | 7 | 15 | 22 | 23 | 6 | 20 | 30 | 33 | 32 | 36 | 35 | 29 | 24 | 28 | 25 | 19 | 31 | 27 | 26 |
| 4 | 2 | 1 | 10 | 12 | 9 | 4 | 5 | 8 | 15 | 3 | 6 | 14 | 16 | 19 | 17 | 20 | 34 | 11 | 18 | 23 | 24 | 7 | 21 | 31 | 28 | 33 | 36 | 35 | 30 | 25 | 29 | 26 | 13 | 32 | 27 | 22 |
| 5 | 7 | 1 | 16 | 18 | 2 | 6 | 8 | 5 | 21 | 10 | 3 | 19 | 13 | 11 | 9 | 15 | 34 | 17 | 12 | 23 | 22 | 4 | 14 | 32 | 31 | 33 | 36 | 35 | 29 | 26 | 25 | 24 | 20 | 30 | 27 | 28 |
| 6 | 4 | 2 | 14 | 16 | 7 | 10 | 11 | 5 | 20 | 3 | 1 | 12 | 13 | 17 | 9 | 18 | 34 | 15 | 8 | 23 | 22 | 6 | 19 | 33 | 30 | 28 | 36 | 35 | 31 | 25 | 24 | 26 | 21 | 32 | 29 | 27 |

Table 3. Test-retest reliability for each subject by Pearson Product Moment Correlation Coefficients. Each coefficient is based on a retest of ten pre-experimentally determined phonemes.

| Subjects: | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| r | 0.93* | 0.99* | 0.85* | 0.99* | 0.99* | 0.99* |

*With eight degrees of freedom, $p \leq 0.01$.[1]

The high correlation coefficients indicate excellent test-retest reliability. All were significantly different from zero at the 0.01 level of confidence.

The Relationship Between Tactile Thresholds and Speech Power of the Phonemes. The relationship between the mean vibrotactile threshold values elicited and the relative speech powers of the tape recorded phonemes was evaluated by Spearman's rho. For the six subjects and the 36 variables a rho of 0.71 was found. The significance of this value is high, $p \leq 0.01$.[2] Thus, a strong relationship between vibrotactile thresholds for spoken phonemes and the relative speech powers of the phonemes is demonstrated.

Table 4 displays the rank order of the subjects' tactile thresholds and shows a comparison to the speech

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[1] Downie and Heath, Basic Statistical Methods, p. 306.

[2] Siegel, Nonparametric Statistics, p. 284.

Table 4. Comparison of rank orders of the phonemes based on mean tactile threshold and on speech power.

| Phoneme | Tactile Rank | Speech Power Rank | Phoneme | Tactile Rank | Speech Power Rank |
|---|---|---|---|---|---|
| u | 1 | 12 | æ | 19 | 5 |
| o | 2 | 6 | v | 20 | 29 |
| ɪ | 3 | 13 | p | 21 | 35 |
| ɛ | 4 | 11 | m | 22 | 20 |
| ŋ | 5 | 18 | n | 23 | 23 |
| ʊ | 6 | 7 | k | 24 | 30 |
| ʌ | 7 | 3 | g | 25 | 28 |
| e | 8 | 4 | tʃ | 26 | 21 |
| i | 9 | 14 | dʒ | 27 | 24 |
| l | 10 | 16 | d | 28 | 34 |
| w | 11 | 22 | b | 29 | 33 |
| au | 12 | 9 | t | 30 | 31 |
| ɔ | 13 | 1 | ð | 31 | 32 |
| ɝ | 14 | 15 | z | 32 | 26 |
| aɪ | 15 | 8 | ʒ | 33 | 25 |
| ɔɪ | 16 | 10 | h | 34 | 36 |
| ɑ | 17 | 2 | ʃ | 35 | 17 |
| j | 18 | 19 | f | 36 | 35 |

power rankings. Again, it can be seen that the degree of relationship is more consistent for the consonant sounds than for the vowels.

## Experiment 2

The purpose of the second experiment was to determine how the subjects judged the tactile distinctive features for each of the phonemes.

The pilot study clearly indicated that three dimensions of vibrotactile discrimination were possible: intensity, duration, and the vibratory pattern of the stimuli. The tactile pattern dimension probably represents "vibratory rate" or frequency.

Limitations of the Experiment. A total of five phonemes could not be included in Experiments 2 and 3. The /s/ and /θ/ were dropped due to the inability to elicit detection thresholds. As previously stated, the effective intensity range of the equipment was restricted to 45 dB (see Appendix 8). As a result, if the /ʃ/ and /f/ sounds were presented at a constant intensity level of 40 dB (re: 1.6 volts for zero dB) these phonemes, in fact, would have been presented below their mean threshold values for the group of subjects. Finally, /h/ was excluded due to a problem with recording noise. When this phoneme was presented at the group mean suprathreshold level of 10 dB (the desired 40 dB stimulus level), a low level recording noise was present and contaminated the signal. Efforts to correct the problem were not successful. In explanation of this, one might consider the fact that the /θ/ was eliminated from Experiment 1 due to its low speech power and high frequency composition. The /h/ phoneme shares the low speech power characteristic, being only three dB above the value for /θ/.

The Tactile Distinctive Features for 33 Phonemes. The tactile distinctive features for the remaining 33 phonemes are presented in a manner so that each cell of Table 5 contains phonemes sharing a set of three identical features. The phonemes were considered to have identical distinctive features if at least five of six subjects selected the same set of features for an individual phoneme.

The /u/ sound, for example, was judged by at least five out of six subjects as having a distinctive feature set of "strong, long, and nonchanging in pattern." This criterion of consistent response (5 out of 6) was not met for the /æ/, /ɝ/, /au/, and /dʒ/ sounds. These phonemes, therefore, are placed in Table 5 between the cells where the source of disagreement was demonstrated. When considering the /æ/ sound, for example, the criterion

Table 5. The 33 English phonemes grouped according to a three dimensional classification of distinctive features (intensity, duration, pattern).

| | Long | | Short | |
|---|---|---|---|---|
| | Non-Changing | Changing | Non-Changing | Changing |
| Strong | /u/ /ɔ/<br>/ɑ/ | /o/ /e/ /i/<br>/aɪ/ /ɔɪ/<br>/l/ /ŋ/ | /ʊ/ /ʌ/ /ɛ//ɝ/<br>/ɪ/ /w/ | |
| | | /æ/ | | /au/ |
| Weak | /m/ /n/ /ʒ/ | /z/ /ð/<br>/tʃ/ | /j/ /v/ /b/<br>/d/ /p/ /t/<br>/k/<br>/g/ | /dʒ/ |

for agreement was met in two dimensions, pattern and duration. There was disagreement on the dimension of intensity. Responses among subjects to /æ/ were not consistent on this dimension.

The validity of the subjects' classification of phonemes on the intensity dimension can be evaluated by using the threshold values for the same phonemes as a criterion (see Table 1 or 2). An inspection of these tables shows that all the vowels and vowel glides are detected at relatively low intensity levels. These phonemes have the 19 lowest detection thresholds as a group. In Table 5, with the exception of /j/, /æ/, and /au/, these same sounds are described as "strong," when they are presented at a constant stimulus level. The consonants are all judged "weak." An intensity level of about 11 dB (re: 1.6 volts) appears to be the cut-off value between the two judgments, strong or weak.

## Experiment 3

In Experiment 2 the phonemes that were described with identical tactile distinctive features (TDF) were identified and displayed together as a cell. The purpose of Experiment 3 was to pair these phonemes in such a manner to determine:

1. If further discriminations are possible between phonemes with the same set of TDF (referred to as _additional discriminations possible_),

2. If phonemes can be judged consistently as "different" by paired comparisons when they did not meet the consistency of judgment criterion of five out of six subjects for TDF (referred to as _other additional discriminations possible_),

3. If phonemes previously described by a different set of TDF are also judged different by paired comparisons (referred to as _validity criterion_).

Table 6 presents a summary of the analyses completed for this experiment.

_Additional Discriminations Possible_. Tables 7 and 8 present the details of paired comparison responses to phonemes in a pair that were indistinguishable from one another in Experiment 2. The pairs in the first column of Table 7 could not be further discriminated, and were judged as "same" by the subjects. The criterion was agreement by at least five out of six subjects. There are 19 such pairs. Column two displays the 14 pairs where further discrimination was possible.

To demonstrate a specific application of the data, consider the TDF set of "long, strong, nonchanging" containing the /u/, /ɔ/ and /a/ phonemes. No further discriminations among these sounds were possible by the criterion of agreement among subjects. Inspection of Table 7 shows that none of the possible three pairing

Table 6. Summary of paired comparisons analyses: Three further evaluations of Tactile Distinctive Feature (TDF) data.

| Purpose of evaluation | Analyses | Table |
|---|---|---|
| I. Additional discriminations by paired comparisons (same TDF, Exp. 2) | 1. Additional discriminations possible with criterion of agreement (5 out of 6) | 7 |
| | 2. Additional discriminations not possible, phonemes judged "same" (5 out of 6 Ss) | 7 |
| | 3. Phonemes not consistently judged "same" nor "different" (criterion of agreement not met) | 8 |
| | 4. Individual subject scores for paired comparison judgments, column 3 | 10 |
| II. Other discriminations possible by paired comparisons (inconsistent TDF, Exp. 2) | 1. Additional discriminations possible with criterion of agreement (5 out of 6) | 9 |
| | 2. Phonemes not consistently judged "same" nor "different" (criterion of agreement not met) | 9 |
| | 3. Additional discriminations not possible, phonemes judged "same" (5 out of 6) | 9 |
| III. Validity criterion by paired comparisons (different TDF, Exp. 2) | 1. TDF judgments supported with criterion of agreement (5 out of 6) column 2 | 11 |
| | 2. TDF judgments not supported with criterion of agreement, column 1 | 11 |
| | 3. Subjects' discrimination scores for identical phonemes in a pair, column 2 | 10 |
| (identical phonemes in a pair) | 1. See data in Appendix XII | 10 |

## Table 7

Paired Comparisons:
Phonemes with Identical Distinctive Features

| Judged "same" | Judged "different" |
|---|---|
| b-d | ŋ-o |
| ɛ-ʊ | w-ʌ |
| aɪ-ɔɪ | p-g |
| ð-z | z-tʃ |
| ʊ-ʌ | j-p |
| m-n | j-k |
| ʌ-ɪ | v-t |
| ɛ-ɪ | p-d |
| ɔ-ɑ | j-g |
| e-aɪ | t-j |
| i-ŋ | p-k |
| g-b | ð-tʃ |
| ʒ-m | v-p |
| k-t | w-ɛ |
| o-ɔɪ | |
| ɔɪ-aɪ | |
| v-j | |
| d-g | |
| ʒ-n | |

Identically described phoneme pairs judged "same" and pairs judged "different" on paired comparisons. Data were based on two trials each for six subjects. Criterion for agreement was by at least five out of six subjects.

Table 8. Phonemes not judged consistently "same" nor "different" by at least five out of six subjects. Data were based on two trials each for six subjects.

l-i
ʒ-n
i-aɪ
l-e
b-v
d-v
b-j
v-k
l-ɔɪ
o-l
K-b

aɪ-o
e-i
k-d
l-aɪ
ɛ-w
v-g
l-ŋ
t-b
t-p
ŋ-e
ŋ-aɪ

ɔɪ-i
g-k
ŋ-ɔɪ
ɔ-u
w-ʊ
ɑ-u
g-t
o-i
o-e
j-d

(/u-ɔ/, /u-a/, /ɔ-a/) appears in column two. The /ɔ-a/ pair does appear in column one, however; indicating that the two phonemes in this pair were judged as being the "same". The other two possible pairs, /u-a/ and /u-ɔ/, appear in Table 8, indicating subject judgments were not consistent.

Just as in Experiment 2, in which a few phonemes were not consistently described on a particular dimension; some pairs in Experiment 3 were not judged consistently by paired comparisons as "same" nor "different." Table 8 shows 32 pairs falling into this category.

*Other Additional Discriminations Possible*. Experiment 2 showed that four phonemes, /ɝ/, /au/, /æ/ and /dʒ/, were not consistently described by TDFs. Therefore, these phonemes were not included in the first two analyses of Experiment 3. To determine if *consistent* discriminations are possible by paired comparisons, each phoneme was paired with a variety of phonemes from different cells.

The results of these comparisons are presented in Table 9. The first column shows two pairs where no discrimination was possible. Column two indicates there are 12 pairs which were not consistently judged "same" nor "different." The criterion of agreement of five out

Table 9

Paired Comparisons:
Phonemes not meeting criterion of agreement for
Tactile Distinctive Features

| Judged "same" | Criterion of Agreement not met* | Judged "different" |
|---|---|---|
| g-dʒ | dʒ-b | ɝ-ɛ |
| e-æ | dʒ-j | ɝ-ʊ |
| | dʒ-k | ɝ-ɪ |
| | dʒ-v | ɝ-ʌ |
| | dʒ-d | ɝ-w |
| | dʒ-t | au-dʒ |
| | æ-l | au-e |
| | æ-aɪ | au-z |
| | æ-ɔɪ | au-v |
| | æ-ŋ | æ-o |
| | æ-ɔ | æ-z |
| | ɝ-au | æ-ð |
| | | æ-ʊ |
| | | æ-ʌ |
| | | æ-ɛ |
| | | p-dʒ |

*Data were based on two trials each for six Ss. Criterion for agreement was by at least five out of six subjects.

of six subjects was not met. The third column shows that 17 pairs were discriminated as "different," indicating further discriminations.

Validity Criterion: Identical Phonemes in a Pair. When each phoneme was compared with itself, for example /i-i/, only two subjects on two different pairs failed to identify the phonemes in the pairs as "same." These data are presented in column one of Table 10.

Validity Criterion: Phonemes in a Pair with Different TDF Sets. Eight randomly chosen phoneme pairs with phonemes in the pair differing on one TDF dimension only; three phoneme pairs differing in two dimensions, and one pair differing in all three dimensions were used to evaluate the judgments made in Experiment 2. It was expected that the subjects would judge these pairs as "different" as these phonemes were previously described by "distinctive" sets in Experiment 2. Table 11 shows the consistency of the subjects' judgments. The /u-U/ pair was the only case of inconsistency. The members of this pair had been distinguished in one dimension only, viz. length, in the previous experiment.

Table 12 presents a summary of all possible discriminations by paired comparisons. These are presented in the inset boxes of each cell. For the TDF

## Table 10
## Paired Comparisons

Each subject's discrimination score for three different types of paired phonemes: (1) identical phonemes in a pair, (2) phonemes differing in one or more dimensions, and (3) different phonemes sharing the same distinctive feature (DF) set. Scored by number of correct responses out of the total possible in each case.

| Subjects | Identical Phonemes | Phonemes differing in one or more dimensions | Different phonemes with same DF set, and percent of discrimination found | |
|---|---|---|---|---|
| $S_1$ | 36/36* | 11/12 | 30/65 | 46% |
| $S_2$ | 36/36 | 10/12 | 27/65 | 41% |
| $S_3$ | 35/36 | 12/12 | 22/65 | 34% |
| $S_4$ | 35/36 | 12/12 | 27/65 | 41% |
| $S_5$ | 36/36 | 12/12 | 28/65 | 43% |
| $S_6$ | 36/36 | 12/12 | 32/65 | 49% |

*This total represents 33 different phonemes paired, with three pairs replicated.

Table 11. **Paired phonemes** with each phoneme in a **pair** described **by a** different **TDF set.***

| Judged "same" | Judged "different" |
|---|---|
| | ɛ-e |
| u-ʊ | a-n |
| | v-n |
| | ɔ-ɛ |
| | i-ɪ |
| | n-ɛ |
| | e-ɔ |
| | n-ɪ |
| | ɔɪ-ɪ |
| | tʃ-t |
| | ɪ-tʃ |

*Data were based on two trials each for six subjects. Criterion for agreement was by at least five our of six subjects.

Table 12. Summary table for the tactile distinctive features for 36 English phonemes. All additional discriminations by paired comparisons are in inset boxes.*

<table>
<tr><th></th><th colspan="2">Long</th><th colspan="2">Short</th></tr>
<tr><th></th><th>Non-changing</th><th>Changing</th><th>Non-changing</th><th>Changing</th></tr>
<tr><td rowspan="3">Strong</td><td>/u/ /ɔ/ /ɑ/</td><td>/o/ /e/ /i/<br>/aɪ/ /ɔɪ/<br>/l/ /ŋ/</td><td>/ʊ/ /ʌ/ /ɛ/<br>/ɪ/ /w/</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">/ɝ/</td></tr>
<tr><td>none</td><td>ŋ-o</td><td>ɝ-ɪ w-ʌ<br>ɝ-ʌ w-ɛ<br>ɝ-w<br>ɝ-ʊ<br>ɝ-ɛ</td><td>none</td></tr>
<tr><td></td><td></td><td>/æ/</td><td></td><td>/au/</td></tr>
<tr><td rowspan="3">Weak</td><td>/m/ /n/ /ʒ/</td><td>/z/ /ð/ /tʃ/</td><td>/j/ /v/ /b/<br>/d/ /p/ /t/<br>/k/ /g/</td><td></td></tr>
<tr><td></td><td></td><td colspan="2">/dʒ/</td></tr>
<tr><td>none</td><td>æ-ð<br>æ-z<br>tʃ-ð<br>tʃ-z</td><td>p-g j-k<br>p-dʒ j-g<br>p-j j-t<br>p-d<br>p-k t-v<br>p-v</td><td>au-dʒ</td></tr>
</table>

*All data were based on two trials each for six subjects. Criterion for agreement was by at least five our of six subjects.

set of "strong, long, nonchanging," no additional discriminations were made. Ten pairs were judged "different" in the set, "weak, short, nonchanging." Inspection of Table 12 shows that the /ɝ/ and /p/ sounds were judged consistently "different" when paired with phonemes in the same cell. It can be hypothesized that these phonemes possess unique distinctive features that were not accounted for in Experiment 2. The unique discriminability of /p/ was supported by spontaneous responses of the subjects during the course of all three experiments.

## Discussion

Basic data relative to vibrotactile thresholds and tactile discriminations of spoken phonemes were provided by this study. The basis for undertaking the research was an interest in vibrotactile information as a supplement to visual communication and to residual auditory function. Thus a significant enhancement of communication success might be realized by persons with significant hearing loss. The validity of this approach was demonstrated by the results of the relevant studies presented in Chapter II (e.g. Pickett, Johnson, Gault). None of these studies, however, evaluated the information that was actually received by the cutaneous sensory receptors of the subjects. In any case, their use of multiple vibrators with the inherent masking effects caused by this approach, would have confounded such an analysis.

With the use of a single, efficient vibrator, the Bimorph, the present study was successful to a significant degree in defining the information received from spoken phonemes via vibrotactile stimulation at the finger tip.

Detection thresholds for 36 phonemes were found. Stimuli provided by utterances of the /s/ and /θ/ phonemes could not elicit responses. Whether or not this can be attributed to limitations within the instrumentation to move the skin at high frequency levels or to the inherent incapability of the cutaneous receptors to receive high frequency stimuli is not resolved. The literature does not provide convincing evidence for either case. Geldard has speculated that the cutaneous receptors have the potential, but as yet a transducer to provide efficient stimulation at high frequencies has not been developed.[1]

The apparent need for transmission systems employing downward frequency transposition for high frequency speech sounds is understandable from the

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[1] Geldard, Journal of General Psychology, 22 (1940), pp. 243-269.

results of this study. Due to the effects of high frequency composition and low speech power, the /θ/, /s/, /ʃ/, /h/ and /f/ sounds were eliminated from full analysis in the present study. Until the problem of stimulating the skin with high frequency stimuli is resolved, tactile information for these particular phonemes cannot be specified.

The TDF task of this study identified tactile characteristics for 33 phonemes on three dimensions: intensity, duration and pattern. Efforts during the pilot study to specify the pattern dimension by such adjective pairs as: rough--smooth, continuous--broken, ascending in pattern--descending in pattern, flat--changing and several other possible pairs provided by the subjects, elicited no consistent agreement among subjects. The TDF's of "changing or nonchanging" pattern did achieve agreement. The writer hypothesizes that given sufficient training in this dimension, subjects could agree upon further refinements for the pattern dimension. On an heuristic basis alone, it would appear that the combined effects of vibratory rate and waveform pattern should present unique identifying information on some of the speech sounds.

The validity of the TDF intensity dimension was supported by the threshold data of the subjects.

Discrimination between vowels versus consonants seems significantly enhanced through the intensity dimension alone.

Although no direct validity criterion for duration dimension was designed for this study, as was the case for intensity, some indirect observations can be made. Inspection of the speaker's spectrograms for each of the recorded phonemes lends considerable validity to the subjects' judgments. Without any metrics involved, even casual observation of the spectrograms clearly and easily dichotomizes the short from long sounds.[1] With the exception of the /au/ sound, the subjects showed agreement with the recorded duration dimension for each phoneme. The speaker's spectrogram for the phoneme /au/ shows it to be longer than the / I/, /n/, /æ/, /m/, /ɜ/, /a/, /e/, /o/ and /u/ sounds which were consistently judged as "long" by the subjects. There is no explanation for this disparity. Appendix 2 presents the duration data from the recording of each of the phonemes.

Finally, the additional discriminations possible by paired comparisons of the phonemes lends credance to

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[1] The recording of the phonemes was guided by Black's relative duration criterion for speech sounds (short-long). The spectrographic analyses verify the success of the effort for each phoneme (see p. 61).

the writer's earlier hypothesis. The dimension of pattern has obviously provided additional tactile clues which are uniquely distinguishable and not accounted for in the adjective pair "changing-nonchanging." The effects of extensive training and resultant familiarity with the vibratory rate and waveform patterns of the phonemes is of significant interest.

# CHAPTER V

# SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

## Summary

Six subjects responded to three tape recorded programs of single, spoken phonemes.

The first program was designed to determine absolute thresholds of detection for the English phonemes by vibrotactile reception. The results indicate that thresholds can be elicited for all the phonemes, with the exception of /s/ and /θ/. The mean threshold data and standard deviations were obtained for the remaining 36 phonemes. The vowel sounds were distributed into a compact range requiring relatively minimal energy for detection. The range for the consonants was considerably larger requiring greater stimulus intensities for detection.

The effect of the relative speech powers and inherent frequency compositions of each of the phonemes was demonstrated. Phonemes with low speech power and basically high frequency composition require more energy for detection.

The agreement among subjects regarding threshold levels was significantly high. Further, significant reliability between test and retest was demonstrated. Low variability among subject responses indicates excellent stability of the stimulus transmission system and subject performance on the threshold task.

Tactile distinctive features were achieved for 33 phonemes on three dimensions: intensity, duration, and stimulus pattern. There was lack of agreement among subjects on determining a TDF set for the /ɝ/, /au/, /æ/ and /dʒ/ sounds.

The validity of subject performance on the intensity dimension was supported by the threshold data for the phonemes.

Additional discriminations were elicited when phonemes were presented by paired comparisons. Phonemes in pairs containing the /ɝ/ and /p/ sounds were consistently judged as "different." These observations suggest that the resolving power of the three dimensional TDF sets is not conclusive.

When phonemes differing in one or more dimensions were presented in pairs, the subjects consistently discriminated the phonemes in a pair as "different," with one exception, /u/-/U/. Thus, a validity criterion was established for the judgements made in the TDF experiment.

## Conclusions

Within the limitations of the instrumentation employed and the design of this study, the following conclusions are warranted:

1. Detection thresholds can be elicited for 36 English phonemes utilizing a single vibrotactile stimulator and without frequency transposition.

2. The /θ/ and /s/ phonemes cannot be detected through cutaneous sensory receptors at the finger tip employing the Clevite Bimorph (model PZT-5B) as a transducer.

3. The tactile stimulus transmission system, incorporating the Bimorph (PZT-5B), does have excellent stability as demonstrated by the low variability among subjects' threshold responses for phonemes.

4. The tactile detection threshold responses for individual phonemes show excellent agreement among subjects and demonstrate high test-retest reliability. There is, however, closer agreement among subjects for the consonant thresholds than for the vowel thresholds.

5. The tactile detection of vowel and vowel-glide phonemes requires less vibromechanical energy than is required for tactile detection of consonants.

6. Tactile threshold responses for English phonemes are inversely related to high frequency composition and low speech power of the respective phonemes.

7. Tactile distinctive features on at least three dimensions (intensity, duration, and pattern) can be described for 33 phonemes. There was, however, lack of agreement among subjects on the intensity dimension for the /au/ and /æ/ phonemes and on the pattern dimension for the /ɝ/ and/dʒ/ phonemes.

8. **Phonemes differing on one or more tactile** distinctive features can be judged consistently as "different" by paired comparisons.

9. Identical phonemes with the same tactile distinctive feature sets can be discriminated consistently as "same" by paired comparisons.

10. Different phonemes with the same tactile distinctive features sets can be discriminated as "different" on 42 percent of the trials by paired comparisons. This finding suggests that the resolving power of the three dimensional tactile distinctive feature sets is not absolutely conclusive.

## Recommendations for Further Research

In view of the findings of this research, the following recommendations for additional research are presented:

1. It is suggested that a study designed to evaluate the role of vibratory rate and waveform of the stimulus events be made. If this could be achieved, perhaps many more tactually received stimulus events could be discriminated. It is hypothesized that the systematic effects of training will significantly influence a subject's ability for tactual discrimination.

2. A study designed to measure the effects of different speakers on subjects' responses is an obvious priority. How does a female voice influence thresholds of detection for the phonemes? Would the TDFs be described in the same manner for persons with varying vocal characteristics? It is clear that the future success of tactile reception of oral speech is contingent upon knowledge of the variability due to speaker effects.

3. A study designed to evaluate visual, tactile and auditory confusions and the relationship of the confusions across the three modalities would have merit. The data from this study indicate that numerous tactile confusions exist when discriminations among certain sets

of phonemes are considered. For example, the /ɔ/, /ɑ/ and /u/ sounds possess identical TDFs and could not be discriminated as different by paired comparisons. Can the visually confused /p/, /b/ and /m/ be tactually discriminated as different from one another? The data from the present study show they can. The possible effect of tactile information on lipreading performance deserves further consideration through systematic study.

4. The influence of vibrotactile information on the hearing handicapped person's voice quality, rate of speaking and syllable stress is another broad area for further research. The potential of taction in providing an improved feedback loop for the profoundly hard of hearing person's own speech would appear to be promising.

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# APPENDICES

# APPENDIX 1

# RESPONSE CHARACTERISTICS OF RECORDING EQUIPMENT

## RESPONSE CHARACTERISTICS OF RECORDING EQUIPMENT

1. Recording microphone. The Electrovoice 654 microphone was placed in the Hearing Aid Test Box (Type 4212) symmetrically opposite to the regulating microphone. The output from the microphone under test was fed directly into the Microphone Amplifier (B & K Type 2604). A 60 dB signal generated from a Beat Frequency Oscillator (B & K Type 1022) into the Hearing Aid Test Box sound field was used in conjunction with the amplifier section of an Audio Frequency Spectrometer (B & K Type 2112) and a Graphic Level Recorder (B & K Type 2305) to record the frequency response curve by the graphic level recorder. The results showed that the Electrovoice 654 was uniform in response (-1 dB, 1000 Hz) from 50 to 15,000 Hertz.

2. Magnecord Tape Recorder (Model 1022 RX). The frequency response characteristics of this tape recorder were evaluated by utilizing an Ampex (7½ ips) Precision Alignment Tape (NAB). The frequency response of the Magnecord tape recorder was found to be relatively uniform from 50 to 1200 Hz, ± 2 dB.

3. Ampex Tape Recorder (Model AG 350). The procedure for determining the frequency response characteristics of this tape recorder were the same as for the

## APPENDIX 1 (continued)

Magnecord. The frequency response of this Ampex recorder was found to be relatively uniform from 50 to 1500 Hertz, ± 1 dB.

4. Ampex Tape Recorder (Model AG 500). The same procedure as described for the Magnecord was also employed in evaluating the frequency response characteristics of this tape recorder. The evaluation showed relatively uniform responses from 50 to 1500 Hertz, + ½ dB and -1 dB.

# APPENDIX 2

# RELATAVE SPEECH POWERS, DURATIONS, AND BASIC FREQUENCY COMPOSITIONS OF 38 RECORDED ENGLISH PHONEMES

## SPEECH POWERS, DURATIONS, AND FREQUENCIES OF PHONEMES

| Phoneme | Relative speech power in dB | Duration in Msecs. | Basic Frequency in Hertz* |
|---|---|---|---|
| ɔ | 28.0 | 550 | 300 |
| ɑ | 27.7 | 420 | 500 |
| ʌ | 27.0 | 292 | 850 |
| e | 27.0 | 360 | 450 |
| æ | 26.9 | 500 | 700 |
| au | 26.7 | 600 | 900 |
| ɔɪ | 25.4 | 540 | 450 |
| ɛ | 25.4 | 240 | 500 |
| u | 24.9 | 575 | 250 |
| o | 26.7 | 542 | 500 |
| ʊ | 26.6 | 230 | 400 |
| aɪ | 25.9 | 500 | 900 |
| ɪ | 24.1 | 220 | 450 |
| i | 23.4 | 550 | 150 |
| ɝ | 23.2 | 200 | 475 |
| l | 20.0 | 450 | 475 |
| ʃ | 19.0 | 560 | 2075 |
| ŋ | 18.6 | 480 | 250 |
| j | 17.5 | 170 | 300 |
| m | 17.1 | 420 | 300 |
| tʃ | 16.2 | 350 | 2800 |
| w | 16.0 | 150 | 450 |
| n | 15.5 | 390 | 300 |
| dʒ | 13.6 | 200 | 500 |
| ʒ | 13.0 | 400 | 225 |
| z | 12.0 | 560 | 250 |
| s | 12.0 | 540 | 6200** |
| g | 11.7 | 150 | 1200 |
| v | 11.7 | 220 | 200 |
| k | 11.1 | 100 | 1000 |
| t | 10.7 | 100 | 3200 |
| ð | 10.4 | 350 | 200 |
| b | 8.4 | 105 | 450 |
| d | 8.4 | 105 | 400 |
| p | 7.7 | 100 | 850 |
| f | 6.9 | 100 | 3200 |
| h | 4.0 | 100 | 1000 |
| θ | 1.0 | 200 | 6500** |

*Basic frequency composition refers to lowest intense energy concentration shown on the spectograms. The specific frequency in Hertz refers to the midpoint of the concentration of energy.

**From Fletcher, "Acoustical Speech Powers," p. 87.

## APPENDIX 3

## BIMORPH LOADING DATA
## AND RESPONSE CHARACTERISTICS

## BIMORPH LOADING DATA*

| Bimorph Model | Size (in inches) | Applied Pressure (in grams) | Voltage Limit |
|---|---|---|---|
| PZT-5H | 0.1 x 1.5 | 15** | 250 |
| PZT-5BN | 1/8 x 1.0 | 15 | 200 |
| PZT-5B*** | 1/8 x 1.25 | 15 | 260 |

*Data is transposed from "Bimorph Design Chart," Technical Paper TP-237. (Bedford, Ohio: Clevite Corporation), March 5, 1969.

**An applied pressure of 15 grams for the purposes of this study was recommended by telephone communication with C. E. Sherrick, Ph.D., Professor of Engineering, Princeton University, January 5, 1970.

***The PZT-5B was chosen for this study because of the higher voltage limit. The PZT-5 series all provide relatively flat frequency response characteristics from 15 to 20,000 Hertz according to the Clevite Corporation Technical Publication PD-9247. The resonant frequency for this model series was computed as 300 kHz from a "Resonant Frequency Nomograph" provided on p. 4 of this publication.

# APPENDIX 4

## FREQUENCY RESPONSE CHARACTERISTICS OF THE TACTILE STIMULUS TRANSMISSION SYSTEM

## FREQUENCY RESPONSE CHARACTERISTICS OF THE TACTILE STIMULUS TRANSMISSION SYSTEM

1. Tape recorder. The frequency response characteristics of the Viking 433 Tape Recorder were evaluated by utilizing an Ampex (7½ ips) Precision Alignment Tape (NAB). The frequency response values observed were: -7 dB at 15 kHz, -3 dB at 12 kHz, -2 dB at 10 kHz, -1 dB at 5 kHz, 0 dB at 2.5 kHz, 0 dB at 1 kHz, +½ dB at 500 Hz, +½ dB at 250 Hz, +½ dB at 100 Hz, and 0 dB at 50 Hz.

2. Loudspeaker. With broad band white noise as a signal, the response characteristics of the Electrovoice SP-12 loudspeaker were evaluated. The white noise was fed into the loudspeaker via the Maico MA-24 audiometer (channel two) with the audiometer dial set at 80 dB. All measurements were made with the experimenter in the sound field at the position of the center of a subject's head using the Sound Level Meter (Bruel and Kjaer, Type 2203) and its associated octave band filter network (Bruel and Kjaer, Type 1613). The following responses were noted: Overall level (C Scale) was not significantly different from 80 dB SPL on three measurements which were each separated by one week's time. Immediately following the first measurement of overall level a frequency spectrum

analysis was also completed, with the following values observed:

| Frequency in Hertz | dB SPL |
|---|---|
| 31.5 | 47 |
| 62.5 | 37 |
| 125 | 49 |
| 250 | 59 |
| 500 | 69.5 |
| 1000 | 70.5 |
| 2000 | 76 |
| 4000 | 75 |
| 8000 | 66.5 |
| 16000 | 45.5 |

3. The Bimorph. The only measure on the response characteristics of the transducer, itself, was the overall sound pressure level values for each of the phonemes auditorally emanating from the Bimorph into the sound field. The Pulse Precision Sound Level Meter (Bruel and Kjaer, Type 2204) with a C scale setting was used for this purpose. The positioning of the sound level meter was approximately three inches directly over the Bimorph. The /ɔ/ sound provided the highest reading, being 54 dB SPL.

# APPENDIX 5

# SUBJECT THRESHOLD DATA FORM

SUBJECT RESPONSE FORM #1

NAME: ____________________

Date: ____________________

Subject #: ____________________

Order: ____________________

THRESHOLD DATA

| Phoneme | A* | D* | A | D | A | D | A | D | $\overline{X}$ |
|---|---|---|---|---|---|---|---|---|---|
| o | | | | | | | | | |
| u | | | | | | | | | |
| ɔ | | | | | | | | | |
| e | | | | | | | | | |
| i | | | | | | | | | |
| ʊ | | | | | | | | | |
| ʌ | | | | | | | | | |
| æ | | | | | | | | | |
| ɛ | | | | | | | | | |
| I | | | | | | | | | |
| aI | | | | | | | | | |
| aʊ | | | | | | | | | |
| ɔɪ | | | | | | | | | |
| w | | | | | | | | | |
| j | | | | | | | | | |
| h | | | | | | | | | |
| l | | | | | | | | | |
| ɝ | | | | | | | | | |
| m | | | | | | | | | |

*Ascending: A. Descending: B.

SUBJECT RESPONSE FORM #1: Name: ________________

(continued)

| Phoneme | A | D | A | D | A | D | A | D | $\bar{X}$ |
|---|---|---|---|---|---|---|---|---|---|
| n | | | | | | | | | |
| ŋ | | | | | | | | | |
| v | | | | | | | | | |
| z | | | | | | | | | |
| ð | | | | | | | | | |
| ʒ | | | | | | | | | |
| f | | | | | | | | | |
| ʃ | | | | | | | | | |
| b | | | | | | | | | |
| d | | | | | | | | | |
| dʒ | | | | | | | | | |
| g | | | | | | | | | |
| p | | | | | | | | | |
| t | | | | | | | | | |
| tʃ | | | | | | | | | |
| k | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |

# APPENDIX 6

# SUBJECT TACTILE DISTINCTIVE FEATURE RESPONSE FORM

SUBJECT RESPONSE FORM #2

NAME: ____________

Date: ________________

Subject #: ________

Order: ___________

| Phoneme | STRONG | MODERATE | WEAK | V. WEAK | SHORT | LONG | CHANGE | NO CHANGE | S's CHOICE |
|---|---|---|---|---|---|---|---|---|---|
| o | | | | | | | | | |
| u | | | | | | | | | |
| ɔ | | | | | | | | | |
| e | | | | | | | | | |
| i | | | | | | | | | |
| ʊ | | | | | | | | | |
| ʌ | | | | | | | | | |
| æ | | | | | | | | | |
| ɛ | | | | | | | | | |
| ɪ | | | | | | | | | |
| aɪ | | | | | | | | | |
| au | | | | | | | | | |
| ɔɪ | | | | | | | | | |
| w | | | | | | | | | |
| j | | | | | | | | | |
| h | | | | | | | | | |
| l | | | | | | | | | |
| ɝ | | | | | | | | | |
| m | | | | | | | | | |

SUBJECT RESPONSE FORM #2.
(continued)

NAME:________________

| Phoneme | STRONG | MODERATE | WEAK | V. WEAK | SHORT | LONG | CHANGE | NO CHANGE | S's CHOICE |
|---|---|---|---|---|---|---|---|---|---|
| n | | | | | | | | | |
| ŋ | | | | | | | | | |
| v | | | | | | | | | |
| z | | | | | | | | | |
| ð | | | | | | | | | |
| ʒ | | | | | | | | | |
| f | | | | | | | | | |
| ʃ | | | | | | | | | |
| b | | | | | | | | | |
| d | | | | | | | | | |
| dʒ | | | | | | | | | |
| g | | | | | | | | | |
| p | | | | | | | | | |
| t | | | | | | | | | |
| tʃ | | | | | | | | | |
| k | | | | | | | | | |
| | | | | | | | | | |
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# APPENDIX 7

# SUBJECT PAIRED COMPARISON RESPONSE FORM

SUBJECT RESPONSE FORM #3.

NAME: ________________

Date: ____________________

Subject #: ____________

Order: ______________

## RESPONSE FORM FOR PAIRED COMPARISONS

| Pair | S/D* | Pair | S/D | Pair | S/D | Pair | S/D | Pair | S/D |
|---|---|---|---|---|---|---|---|---|---|
| ɔ-ɑ | | ʒ-n | | ɑ-ɑ | | t-j | | aɪ-o | |
| u-u | | ð-z | | i-i | | z-tʃ | | l-l | |
| ŋ-o | | ɪ-tʃ | | ɛ-æ | | v-v | | æ -z | |
| e-aɪ | | dʒ-ʊ | | ʊ-ʌ | | m-m | | u-ʊ | |
| aɪ-ɑɪ | | g-b | | v-v | | w-ʊ | | æ-æ | |
| e-e | | p-g | | ð-æ | | i-aɪ | | m-n | |
| ɔɪ -i | | tʃ-t | | ɔ-ɔ | | p-dʒ | | ʊ-ʌ | |
| l-i | | dʒ-k | | ɝ-ɝ | | g-g | | au-e | |
| i- ŋ | | g-k | | p-p | | l-aɪ | | v-n | |
| ɪ-i | | ɔ-æ | | ɝ-ɪ | | ʒ-m | | æ -v | |
| ʊ - ʊ | | au-z | | ɝ-ʌ | | -u | | dʒ-d | |
| ʊ-æ | | z-e | | e-i | | ʒ-ʒ | | ɛ-ɝ | |
| ʌ-ʌ | | ɑ -n | | b-b | | k-t | | ʌ-ɪ | |
| ɛ-ʊ | | æ -l | | v-p | | dʒ-dʒ | | o -l | |
| æ-ʌ | | ɔɪ-ɔɪ | | z-z | | ŋ-ŋ | | v-k | |
| æ-æ | | ŋ-ɔɪ | | k-d | | ɛ -w | | l-e | |
| w- ʌ | | b-dʒ | | ɔ -u | | g-t | | n-n | |
| ɛ-ɛ | | dʒ -au | | t-dʒ | | p-k | | v-g | |
| w- ɛ | | j-dʒ | | k-dʒ | | ɔ-ɛ | | æ-æ | |

*Same: S. Different: D.

SUBJECT RESPONSE FORM #3.
(continued)

NAME: ________________

| Pair | S/D | Pair | S/D | Pair | S/D | | | | |
|---|---|---|---|---|---|---|---|---|---|
| b-v | | ɛ-ɪ | | ŋ-æ | | | | | |
| l-ŋ | | t-t | | k-k | | | | | |
| o-o | | d-v | | v-j | | | | | |
| æ-ʌ | | p-b | | d-g | | | | | |
| b-j | | p-d | | k-b | | | | | |
| e-æ | | j-j | | j-k | | | | | |
| j-g | | o-ɔɪ | | ð-tʃ | | | | | |
| w-w | | ɔɪ-aɪ | | b-d | | | | | |
| ɔɪ-ɪ | | d-d | | t-p | | | | | |
| t-b | | ŋ-e | | ɝ-ʊ | | | | | |
| g-dʒ | | l-ɔɪ | | ɪ-ɛ | | | | | |
| g-g | | ɝ-w | | i-i | | | | | |
| ɝ-au | | ŋ-aɪ | | j-p | | | | | |
| o-e | | n-ɪ | | n-z | | | | | |
| aɪ-aɪ | | tʃ-tʃ | | au-v | | | | | |
| v-t | | j-d | | au-æ | | | | | |
| aɪ-æ | | o-i | | e-ɔ | | | | | |
| au-au | | æ-o | | | | | | | |
| ð-ð | | ɔɪ-æ | | | | | | | |

# APPENDIX 8

# EQUIPMENT CALIBRATION

## EQUIPMENT CALIBRATION

The equipment was calibrated prior to each of the three experiments. The Maico MA-24 audiometer was calibrated to the transducer (Clevite Bimorph, PZT-5B) by taking voltage measurements across the electrical terminals to the Bimorph. The voltage measurements were made with Tektronix 561A Oscilloscope. The 1000 Hz calibration tone from the master tape provided the stimulus tone. No systematic differences were found during the three test measurements from the values reported below:

| Attenuator dial setting | Voltage readings |
|---|---|
| 30 dB | 0.50 volts |
| 35 | 0.85 |
| 40 | 1.6 |
| 45 | 2.5 |
| 50 | 5.0 |
| 55 | 8.5 |
| 60 | 15.5 |
| 65 | 25.0 |
| 70 | 50.0 |
| 75 | 85.0 |
| 80 | 150.0 |
| 85 | 250.0 |

The linearity of the MA-24 attenuator dial was checked using the Sound Level Meter (Bruel and Kjaer, Type 2203) in conjunction with the Artificial Ear (Bruel and Kjaer, Type 4152). The TDH-39 earphone housed in a MX 41/AR biscuit type cushion was connected to the 6cc coupler of the artificial ear and this in turn was coupled to the sound level meter, the following values were noted:

| Attentuator dial setting | Differences from 110 dB SPL |
|---|---|
| 100 dB | -0.30 |
| 90 | -0.40 |
| 85 | -0.40 |
| 80 | -0.50 |
| 75 | -0.50 |
| 70 | -0.60 |
| 65 | -0.60 |
| 60 | -0.60 |
| 55 | -0.50 |
| 50 | -0.70 |
| 45 | -0.70 |
| 40 | -0.80 |
| 35 | -0.70 |
| 30 | -0.80 |
| 25 | -0.90 |
| 20 | -0.80 |

Vernier (1 dB Steps)

| | |
|---|---|
| 61 | no error |
| 62 | +0.10 |
| 63 | no error |
| 64 | no error |
| 65 | -0.10 |

# APPENDIX 9

# THRESHOLD RESPONSE DATA

Threshold data are presented by phoneme "number." Following is the phoneme order for reporting subjects' responses, pages 156-161.

1. o
2. u
3. ɔ
4. ɑ
5. e
6. i
7. ʊ
8. ʌ
9. æ
10. ɛ
11. ɪ
12. aɪ
13. au
14. ɔɪ
15. w
16. j
17. h
18. l
19. ɝ
20. m
21. n
22. ŋ
23. v
24. z
25. ð
26. ʒ
27. f
28. ʃ
29. b
30. d
31. dʒ
32. g
33. p
34. t
35. tʃ
36. k

Raw data: SUBJECT ONE. Threshold responses in dB (re 1.6 volts) for four ascending and four descending series

Ascending: A Descending: D

| Phoneme # | A | D | A | D | A | D | A | D | $\bar{X}$ | S.D. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 6 | 4 | 5 | 3 | 3 | 2 | 3 | 3 | 3.6 | 1.30 |
| 2. | 4 | 2 | 4 | 3 | 4 | 3 | 4 | 4 | 3.5 | 0.75 |
| 3. | 8 | 7 | 9 | 8 | 9 | 6 | 9 | 7 | 7.9 | 1.12 |
| 4. | 12 | 11 | 12 | 11 | 12 | 10 | 12 | 11 | 11.4 | 0.74 |
| 5. | 8 | 6 | 7 | 5 | 7 | 5 | 6 | 4 | 6.0 | 1.30 |
| 6. | 7 | 5 | 7 | 6 | 5 | 4 | 6 | 5 | 5.6 | 1.06 |
| 7. | 7 | 6 | 8 | 7 | 7 | 6 | 7 | 6 | 6.8 | 0.71 |
| 8. | 9 | 7 | 8 | 8 | 9 | 7 | 8 | 6 | 7.8 | 1.03 |
| 9. | 13 | 11 | 12 | 12 | 12 | 11 | 12 | 12 | 11.9 | 0.64 |
| 10. | 5 | 3 | 5 | 4 | 5 | 3 | 4 | 4 | 4.1 | 0.83 |
| 11. | 3 | 2 | 4 | 2 | 4 | 1 | 3 | 1 | 2.5 | 1.19 |
| 12. | 12 | 10 | 11 | 10 | 11 | 11 | 11 | 11 | 10.9 | 0.64 |
| 13. | 8 | 7 | 8 | 6 | 8 | 7 | 9 | 7 | 7.5 | 0.92 |
| 14. | 9 | 7 | 9 | 7 | 8 | 6 | 8 | 7 | 7.6 | 1.06 |
| 15. | 10 | 9 | 11 | 8 | 10 | 7 | 11 | 7 | 9.1 | 1.64 |
| 16. | 13 | 12 | 14 | 13 | 14 | 12 | 13 | 11 | 12.7 | 1.03 |
| 17. | 32 | 30 | 30 | 29 | 31 | 30 | 32 | 28 | 30.2 | 1.39 |
| 18. | 13 | 12 | 13 | 11 | 12 | 10 | 13 | 11 | 11.9 | 1.12 |
| 19. | 9 | 7 | 9 | 7 | 9 | 8 | 10 | 8 | 8.4 | 1.06 |
| 20. | 14 | 12 | 15 | 13 | 14 | 12 | 14 | 13 | 13.6 | 1.06 |
| 21. | 17 | 15 | 16 | 16 | 16 | 15 | 16 | 14 | 15.6 | 0.92 |
| 22. | 4 | 3 | 3 | 2 | 4 | 2 | 3 | 1 | 2.7 | 1.03 |
| 23. | 14 | 13 | 14 | 12 | 13 | 11 | 13 | 11 | 12.6 | 1.19 |
| 24. | 26 | 25 | 25 | 24 | 25 | 24 | 25 | 23 | 24.6 | 0.92 |
| 25. | 24 | 23 | 24 | 25 | 23 | 23 | 23 | 23 | 23.5 | 0.75 |
| 26. | 29 | 28 | 30 | 27 | 29 | 26 | 28 | 26 | 27.9 | 1.46 |
| 27. | 44 | 43 | 45 | 44 | 45 | 45 | 45 | 45 | 44.5 | 0.76 |
| 28. | 44 | 43 | 42 | 42 | 42 | 42 | 42 | 42 | 42.4 | 0.74 |
| 29. | 25 | 23 | 26 | 24 | 25 | 23 | 24 | 22 | 24.0 | 1.31 |
| 30. | 22 | 21 | 21 | 20 | 22 | 21 | 23 | 21 | 21.4 | 0.92 |
| 31. | 22 | 20 | 22 | 19 | 22 | 19 | 21 | 18 | 20.4 | 1.60 |
| 32. | 21 | 20 | 22 | 20 | 22 | 19 | 22 | 19 | 20.6 | 1.30 |
| 33. | 16 | 14 | 15 | 13 | 15 | 13 | 15 | 14 | 14.4 | 1.06 |
| 34. | 24 | 22 | 24 | 21 | 24 | 23 | 21 | 23 | 22.7 | 1.28 |
| 35. | 18 | 17 | 19 | 16 | 18 | 15 | 17 | 16 | 17.0 | 1.31 |
| 36. | 17 | 17 | 17 | 16 | 17 | 14 | 15 | 15 | 16.0 | 1.20 |

Raw data: SUBJECT TWO. Threshold responses in dB (re 1.6 volts) for four ascending and four descending series.

Ascending: A Descending: D

| Phoneme # | A | D | A | D | A | D | A | D | $\bar{X}$ | S.D. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 4 | 2 | 4 | 2 | 4 | 2 | 5 | 4 | 3.4 | 1.19 |
| 2. | 5 | 4 | 6 | 3 | 6 | 3 | 7 | 4 | 4.8 | 1.49 |
| 3. | 12 | 11 | 12 | 10 | 12 | 10 | 12 | 9 | 11.0 | 1.19 |
| 4. | 13 | 12 | 14 | 12 | 13 | 11 | 14 | 11 | 12.5 | 1.19 |
| 5. | 10 | 9 | 11 | 8 | 12 | 9 | 11 | 7 | 9.6 | 1.68 |
| 6. | 7 | 6 | 7 | 7 | 7 | 7 | 8 | 6 | 6.9 | 0.64 |
| 7. | 5 | 4 | 6 | 3 | 6 | 4 | 5 | 4 | 4.6 | 1.06 |
| 8. | 6 | 6 | 7 | 6 | 7 | 5 | 5 | 3 | 5.6 | 1.30 |
| 9. | 13 | 12 | 13 | 11 | 14 | 13 | 13 | 12 | 12.6 | 0.92 |
| 10. | 8 | 7 | 9 | 7 | 8 | 7 | 7 | 7 | 7.5 | 0.75 |
| 11. | 7 | 6 | 6 | 5 | 7 | 5 | 7 | 5 | 6.0 | 0.92 |
| 12. | 9 | 8 | 8 | 7 | 9 | 9 | 9 | 9 | 8.5 | 0.75 |
| 13. | 10 | 8 | 11 | 7 | 12 | 8 | 9 | 8 | 9.1 | 1.73 |
| 14. | 11 | 11 | 12 | 11 | 11 | 11 | 12 | 11 | 11.2 | 0.46 |
| 15. | 10 | 10 | 10 | 9 | 11 | 9 | 12 | 9 | 10.0 | 1.07 |
| 16. | 10 | 12 | 12 | 12 | 13 | 12 | 12 | 13 | 12.0 | 0.92 |
| 17. | 30 | 28 | 29 | 29 | 31 | 29 | 30 | 28 | 29.2 | 1.04 |
| 18. | 5 | 4 | 5 | 5 | 5 | 4 | 5 | 5 | 4.7 | 0.46 |
| 19. | 14 | 12 | 13 | 11 | 12 | 12 | 12 | 10 | 12.0 | 1.19 |
| 20. | 21 | 20 | 21 | 21 | 21 | 20 | 20 | 20 | 20.5 | 0.53 |
| 21. | 22 | 20 | 21 | 20 | 20 | 21 | 22 | 21 | 20.9 | 0.83 |
| 22. | 6 | 5 | 6 | 4 | 7 | 5 | 6 | 4 | 5.0 | 0.75 |
| 23. | 15 | 14 | 16 | 13 | 16 | 14 | 16 | 14 | 14.7 | 1.16 |
| 24. | 25 | 24 | 26 | 23 | 25 | 24 | 25 | 24 | 24.5 | 0.93 |
| 25. | 24 | 23 | 24 | 22 | 23 | 23 | 23 | 23 | 23.1 | 0.64 |
| 26. | 28 | 26 | 28 | 26 | 27 | 27 | 28 | 27 | 27.4 | 1.06 |
| 27. | 45 | 44 | 44 | 43 | 43 | 43 | 45 | 45 | 44.0 | 0.92 |
| 28. | 44 | 42 | 43 | 42 | 43 | 42 | 44 | 43 | 42.9 | 0.83 |
| 29. | 25 | 24 | 25 | 25 | 25 | 24 | 25 | 23 | 24.5 | 0.75 |
| 30. | 22 | 20 | 23 | 20 | 23 | 20 | 22 | 19 | 21.1 | 1.55 |
| 31. | 21 | 20 | 22 | 22 | 22 | 20 | 20 | 18 | 20.6 | 1.41 |
| 32. | 18 | 17 | 19 | 17 | 19 | 18 | 18 | 17 | 17.9 | 0.83 |
| 33. | 15 | 14 | 14 | 13 | 14 | 14 | 15 | 13 | 14.0 | 0.53 |
| 34. | 22 | 21 | 22 | 21 | 23 | 22 | 22 | 21 | 21.8 | 0.71 |
| 35. | 21 | 20 | 22 | 20 | 20 | 20 | 20 | 20 | 20.4 | 0.74 |
| 36. | 19 | 19 | 19 | 18 | 19 | 17 | 18 | 17 | 18.3 | 0.89 |

Raw data: SUBJECT THREE. Threshold responses in dB (re 1.6 volts) for four ascending and four descending series.

Ascending: A Descending: D

| Phoneme # | A | D | A | D | A | D | A | D | $\bar{X}$ | S.D. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 7 | 5 | 7 | 6 | 6 | 5 | 5 | 5 | 5.7 | 0.89 |
| 2. | 7 | 5 | 7 | 5 | 6 | 4 | 5 | 6 | 5.6 | 1.06 |
| 3. | 10 | 9 | 11 | 10 | 13 | 8 | 13 | 7 | 10.1 | 2.17 |
| 4. | 14 | 14 | 14 | 13 | 14 | 14 | 14 | 13 | 13.7 | 0.46 |
| 5. | 9 | 8 | 10 | 7 | 10 | 7 | 10 | 8 | 8.6 | 1.30 |
| 6. | 11 | 10 | 12 | 9 | 11 | 9 | 12 | 9 | 10.4 | 1.30 |
| 7. | 8 | 5 | 8 | 4 | 8 | 5 | 7 | 5 | 6.2 | 1.67 |
| 8. | 11 | 10 | 11 | 9 | 12 | 9 | 10 | 8 | 10.0 | 1.31 |
| 9. | 12 | 12 | 12 | 9 | 11 | 9 | 10 | 9 | 10.5 | 1.41 |
| 10. | 5 | 4 | 5 | 3 | 4 | 2 | 4 | 4 | 3.9 | 0.99 |
| 11. | 8 | 7 | 7 | 6 | 8 | 7 | 8 | 6 | 7.1 | 0.83 |
| 12. | 11 | 10 | 11 | 9 | 10 | 10 | 10 | 10 | 10.1 | 0.64 |
| 13. | 10 | 10 | 11 | 11 | 11 | 9 | 10 | 8 | 10.0 | 1.70 |
| 14. | 12 | 11 | 13 | 12 | 13 | 11 | 13 | 10 | 11.9 | 1.13 |
| 15. | 12 | 10 | 12 | 10 | 13 | 10 | 13 | 10 | 11.2 | 1.39 |
| 16. | 14 | 13 | 13 | 10 | 13 | 10 | 12 | 12 | 12.1 | 1.46 |
| 17. | 29 | 28 | 29 | 28 | 29 | 27 | 29 | 27 | 28.2 | 0.89 |
| 18. | 8 | 7 | 7 | 7 | 9 | 9 | 10 | 10 | 8.3 | 1.30 |
| 19. | 12 | 10 | 12 | 10 | 11 | 10 | 12 | 9 | 10.7 | 1.16 |
| 20. | 20 | 17 | 21 | 17 | 22 | 17 | 20 | 18 | 19.0 | 2.00 |
| 21. | 20 | 17 | 21 | 17 | 20 | 16 | 20 | 19 | 19.6 | 3.46 |
| 22. | 9 | 7 | 9 | 7 | 9 | 7 | 9 | 8 | 8.1 | 0.99 |
| 23. | 14 | 13 | 14 | 12 | 14 | 13 | 13 | 12 | 13.1 | 0.83 |
| 24. | 23 | 22 | 24 | 22 | 22 | 22 | 22 | 20 | 22.1 | 1.12 |
| 25. | 28 | 27 | 28 | 26 | 29 | 26 | 28 | 26 | 27.2 | 1.16 |
| 26. | 26 | 25 | 26 | 26 | 26 | 24 | 26 | 23 | 25.2 | 1.16 |
| 27. | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45.0 | 0.00 |
| 28. | 43 | 42 | 44 | 44 | 45 | 44 | 45 | 43 | 43.7 | 1.03 |
| 29. | 23 | 22 | 23 | 21 | 22 | 20 | 23 | 23 | 22.1 | 1.12 |
| 30. | 22 | 20 | 21 | 21 | 20 | 19 | 22 | 19 | 20.5 | 1.19 |
| 31. | 24 | 23 | 23 | 20 | 22 | 20 | 20 | 20 | 21.5 | 1.69 |
| 32. | 21 | 20 | 23 | 19 | 22 | 19 | 22 | 19 | 20.6 | 1.60 |
| 33. | 14 | 12 | 15 | 10 | 14 | 11 | 14 | 12 | 12.7 | 1.75 |
| 34. | 25 | 24 | 25 | 23 | 23 | 22 | 22 | 22 | 23.2 | 1.28 |
| 35. | 22 | 22 | 22 | 21 | 22 | 20 | 22 | 20 | 21.3 | 0.92 |
| 36. | 21 | 20 | 23 | 20 | 21 | 20 | 21 | 20 | 20.8 | 1.03 |

Raw data: <u>SUBJECT FOUR</u>. Threshold responses in dB (re 1.6 volts) for four ascending and four descending series.

Ascending: A Descending: D

| Phoneme # | A | D | A | D | A | D | A | D | $\bar{X}$ | S.D. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 4 | 3 | 5 | 3 | 5 | 2 | 5 | 3 | 3.8 | 1.16 |
| 2. | 0 | -2 | 0 | -1 | 0 | -1 | 0 | 0 | -1.5 | 0.75 |
| 3. | 7 | 6 | 7 | 5 | 7 | 6 | 8 | 6 | 6.5 | 0.92 |
| 4. | 11 | 10 | 10 | 9 | 9 | 9 | 9 | 9 | 9.5 | 0.75 |
| 5. | 7 | 6 | 8 | 5 | 5 | 4 | 8 | 4 | 5.9 | 1.64 |
| 6. | 6 | 6 | 6 | 4 | 5 | 4 | 6 | 4 | 5.1 | 0.99 |
| 7. | 6 | 5 | 6 | 4 | 6 | 4 | 6 | 5 | 5.3 | 0.87 |
| 8. | 7 | 6 | 7 | 4 | 5 | 5 | 6 | 5 | 5.6 | 1.06 |
| 9. | 12 | 10 | 9 | 9 | 10 | 10 | 10 | 10 | 10.0 | 0.92 |
| 10. | 5 | 3 | 3 | 2 | 4 | 4 | 5 | 5 | 3.9 | 1.12 |
| 11. | 7 | 5 | 5 | 4 | 6 | 5 | 5 | 5 | 5.3 | 0.87 |
| 12. | 12 | 10 | 10 | 9 | 10 | 9 | 11 | 8 | 9.9 | 1.25 |
| 13. | 12 | 10 | 11 | 10 | 10 | 10 | 10 | 10 | 10.4 | 0.74 |
| 14. | 12 | 12 | 12 | 11 | 12 | 10 | 12 | 12 | 11.6 | 0.74 |
| 15. | 11 | 10 | 11 | 11 | 11 | 10 | 11 | 9 | 10.5 | 0.75 |
| 16. | 13 | 12 | 14 | 11 | 13 | 12 | 13 | 10 | 12.3 | 1.28 |
| 17. | 32 | 30 | 32 | 30 | 32 | 31 | 32 | 30 | 31.1 | 0.99 |
| 18. | 8 | 8 | 9 | 9 | 8 | 7 | 7 | 5 | 7.6 | 1.30 |
| 19. | 12 | 11 | 12 | 10 | 12 | 11 | 12 | 10 | 11.3 | 0.87 |
| 20. | 19 | 18 | 19 | 17 | 19 | 17 | 16 | 16 | 17.6 | 1.30 |
| 21. | 19 | 18 | 19 | 18 | 19 | 16 | 17 | 16 | 17.8 | 1.28 |
| 22. | 5 | 4 | 6 | 4 | 7 | 5 | 7 | 5 | 5.4 | 1.19 |
| 23. | 14 | 12 | 14 | 13 | 14 | 13 | 14 | 13 | 13.4 | 0.74 |
| 24. | 22 | 20 | 21 | 20 | 23 | 20 | 22 | 21 | 21.1 | 1.12 |
| 25. | 19 | 18 | 20 | 18 | 20 | 19 | 20 | 20 | 19.3 | 0.89 |
| 26. | 27 | 25 | 28 | 25 | 25 | 24 | 25 | 25 | 25.6 | 1.19 |
| 27. | 45 | 43 | 44 | 43 | 43 | 43 | 43 | 43 | 43.4 | 0.74 |
| 28. | 45 | 42 | 43 | 42 | 43 | 43 | 43 | 43 | 43.0 | 0.93 |
| 29. | 21 | 20 | 21 | 18 | 20 | 19 | 21 | 19 | 19.9 | 1.13 |
| 30. | 17 | 17 | 19 | 16 | 18 | 18 | 18 | 18 | 17.9 | 0.99 |
| 31. | 21 | 20 | 20 | 18 | 20 | 18 | 19 | 20 | 19.5 | 1.07 |
| 32. | 19 | 17 | 19 | 19 | 18 | 17 | 19 | 18 | 18.0 | 0.93 |
| 33. | 10 | 9 | 10 | 9 | 10 | 10 | 10 | 10 | 9.8 | 0.46 |
| 34. | 24 | 22 | 23 | 21 | 22 | 22 | 22 | 21 | 22.1 | 0.99 |
| 35. | 20 | 18 | 20 | 19 | 20 | 17 | 20 | 18 | 19.0 | 1.19 |
| 36. | 18 | 17 | 17 | 16 | 18 | 17 | 18 | 16 | 17.1 | 0.83 |

Raw data: <u>SUBJECT FIVE.</u> Threshold responses in dB (re 1.6 volts) for four ascending and four descending series.

Ascending: A Descending D

| Phoneme # | A | D | A | D | A | D | A | D | $\bar{X}$ | S.D. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 7 | 5 | 7 | 6 | 7 | 4 | 7 | 5 | 6.0 | 1.19 |
| 2. | 3 | 1 | 4 | 0 | 3 | 2 | 3 | 0 | 2.0 | 1.51 |
| 3. | 12 | 10 | 12 | 9 | 11 | 10 | 11 | 10 | 10.6 | 1.06 |
| 4. | 13 | 11 | 13 | 11 | 12 | 11 | 12 | 11 | 11.7 | 0.89 |
| 5. | 5 | 4 | 6 | 3 | 5 | 2 | 4 | 1 | 3.7 | 1.67 |
| 6. | 7 | 6 | 7 | 5 | 7 | 4 | 6 | 4 | 5.7 | 1.28 |
| 7. | 7 | 6 | 7 | 6 | 6 | 5 | 6 | 5 | 6.0 | 0.75 |
| 8. | 7 | 5 | 6 | 4 | 6 | 3 | 6 | 2 | 4.9 | 1.73 |
| 9. | 14 | 13 | 14 | 12 | 15 | 13 | 15 | 12 | 13.5 | 1.19 |
| 10. | 7 | 6 | 8 | 5 | 9 | 6 | 8 | 6 | 6.9 | 1.36 |
| 11. | 5 | 3 | 7 | 2 | 6 | 2 | 5 | 4 | 4.2 | 1.83 |
| 12. | 13 | 11 | 12 | 11 | 13 | 11 | 13 | 11 | 11.9 | 0.99 |
| 13. | 10 | 9 | 10 | 8 | 10 | 9 | 11 | 7 | 9.2 | 1.28 |
| 14. | 9 | 8 | 9 | 7 | 9 | 7 | 8 | 6 | 7.9 | 1.12 |
| 15. | 7 | 6 | 8 | 6 | 8 | 5 | 7 | 5 | 6.5 | 1.19 |
| 16. | 11 | 10 | 12 | 11 | 10 | 9 | 10 | 8 | 10.1 | 1.25 |
| 17. | 32 | 30 | 30 | 29 | 30 | 29 | 30 | 29 | 29.9 | 0.99 |
| 18. | 12 | 10 | 12 | 9 | 11 | 10 | 11 | 10 | 10.6 | 1.06 |
| 19. | 10 | 7 | 10 | 7 | 10 | 8 | 10 | 9 | 8.9 | 1.36 |
| 20. | 16 | 15 | 15 | 14 | 15 | 14 | 15 | 15 | 14.9 | 0.64 |
| 21. | 15 | 14 | 15 | 13 | 14 | 12 | 14 | 13 | 13.7 | 1.03 |
| 22. | 5 | 4 | 5 | 3 | 5 | 4 | 6 | 4 | 4.5 | 0.93 |
| 23. | 12 | 10 | 10 | 9 | 11 | 8 | 10 | 8 | 9.7 | 1.39 |
| 24. | 24 | 22 | 23 | 21 | 23 | 21 | 23 | 22 | 22.4 | 1.06 |
| 25. | 23 | 22 | 23 | 21 | 23 | 21 | 23 | 21 | 22.1 | 0.99 |
| 26. | 24 | 23 | 24 | 22 | 23 | 22 | 24 | 22 | 23.0 | 0.92 |
| 27. | 43 | 43 | 45 | 45 | 45 | 45 | 45 | 45 | 44.5 | 0.92 |
| 28. | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44.0 | 0.00 |
| 29. | 20 | 20 | 22 | 21 | 22 | 21 | 23 | 21 | 21.2 | 1.03 |
| 30. | 20 | 18 | 19 | 17 | 19 | 17 | 19 | 18 | 18.4 | 1.06 |
| 31. | 19 | 17 | 18 | 16 | 18 | 17 | 19 | 18 | 17.7 | 1.03 |
| 32. | 18 | 16 | 18 | 15 | 17 | 16 | 17 | 16 | 16.6 | 1.06 |
| 33. | 14 | 12 | 14 | 13 | 14 | 12 | 14 | 11 | 13.0 | 1.19 |
| 34. | 22 | 21 | 23 | 20 | 23 | 21 | 23 | 21 | 21.7 | 1.16 |
| 35. | 20 | 18 | 20 | 17 | 19 | 18 | 19 | 19 | 18.7 | 1.03 |
| 36. | 22 | 20 | 21 | 19 | 21 | 19 | 21 | 19 | 20.2 | 1.16 |

Raw data: SUBJECT SIX. Threshold responses in dB (re 1.6 volts) for four ascending and four descending series.

Ascending: A Descending: D

| Phoneme # | A | D | A | D | A | D | A | D | $\bar{X}$ | S.D. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 9 | 7 | 9 | 7 | 9 | 8 | 9 | 7 | 8.1 | 0.99 |
| 2. | 7 | 6 | 7 | 6 | 8 | 7 | 7 | 7 | 6.9 | 0.64 |
| 3. | 12 | 11 | 11 | 11 | 12 | 12 | 12 | 11 | 11.5 | 0.53 |
| 4. | 13 | 11 | 12 | 11 | 13 | 11 | 12 | 11 | 11.8 | 0.87 |
| 5. | 8 | 7 | 10 | 9 | 11 | 9 | 11 | 8 | 9.1 | 1.46 |
| 6. | 11 | 9 | 10 | 9 | 11 | 8 | 11 | 9 | 9.8 | 1.16 |
| 7. | 11 | 9 | 10 | 8 | 11 | 9 | 11 | 9 | 9.8 | 1.16 |
| 8. | 10 | 8 | 9 | 7 | 9 | 7 | 9 | 8 | 8.4 | 1.06 |
| 9. | 16 | 14 | 15 | 14 | 16 | 15 | 15 | 14 | 14.9 | 0.83 |
| 10. | 9 | 8 | 9 | 7 | 9 | 7 | 8 | 6 | 7.9 | 1.12 |
| 11. | 8 | 7 | 7 | 6 | 7 | 6 | 7 | 6 | 6.8 | 0.70 |
| 12. | 12 | 11 | 12 | 10 | 12 | 9 | 12 | 9 | 10.9 | 1.36 |
| 13. | 13 | 11 | 12 | 10 | 12 | 10 | 12 | 10 | 11.3 | 1.16 |
| 14. | 14 | 12 | 14 | 11 | 13 | 10 | 12 | 10 | 12.0 | 1.60 |
| 15. | 11 | 9 | 10 | 8 | 10 | 9 | 10 | 9 | 9.5 | 0.92 |
| 16. | 14 | 13 | 15 | 13 | 14 | 13 | 15 | 13 | 13.8 | 0.87 |
| 17. | 33 | 30 | 33 | 30 | 32 | 31 | 32 | 32 | 31.6 | 1.19 |
| 18. | 12 | 11 | 12 | 11 | 12 | 11 | 13 | 11 | 11.6 | 0.74 |
| 19. | 10 | 9 | 10 | 9 | 10 | 8 | 11 | 8 | 9.4 | 1.06 |
| 20. | 18 | 16 | 19 | 17 | 19 | 16 | 18 | 16 | 17.4 | 1.30 |
| 21. | 18 | 17 | 17 | 15 | 17 | 14 | 17 | 15 | 16.3 | 1.39 |
| 22. | 9 | 7 | 9 | 8 | 9 | 9 | 9 | 7 | 8.4 | 0.92 |
| 23. | 15 | 14 | 15 | 13 | 15 | 13 | 14 | 13 | 14.0 | 0.92 |
| 24. | 25 | 23 | 24 | 23 | 25 | 24 | 26 | 24 | 24.3 | 1.03 |
| 25. | 23 | 22 | 23 | 21 | 24 | 21 | 24 | 21 | 22.4 | 1.30 |
| 26. | 23 | 21 | 22 | 21 | 23 | 20 | 22 | 21 | 21.6 | 1.06 |
| 27. | 45 | 44 | 45 | 43 | 44 | 44 | 45 | 44 | 44.3 | 0.71 |
| 28. | 44 | 43 | 44 | 43 | 44 | 43 | 44 | 44 | 43.6 | 0.52 |
| 29. | 24 | 23 | 25 | 22 | 24 | 21 | 23 | 22 | 23.0 | 1.31 |
| 30. | 22 | 20 | 22 | 20 | 21 | 20 | 21 | 20 | 20.8 | 0.89 |
| 31. | 21 | 19 | 20 | 19 | 19 | 19 | 19 | 18 | 19.3 | 0.89 |
| 32. | 22 | 21 | 22 | 20 | 22 | 19 | 21 | 19 | 20.8 | 1.28 |
| 33. | 16 | 15 | 16 | 16 | 16 | 15 | 16 | 14 | 15.5 | 0.76 |
| 34. | 25 | 24 | 26 | 23 | 25 | 24 | 25 | 22 | 24.3 | 1.28 |
| 35. | 23 | 22 | 22 | 21 | 23 | 22 | 24 | 22 | 22.4 | 0.92 |
| 36. | 22 | 20 | 24 | 20 | 23 | 21 | 24 | 21 | 21.9 | 1.64 |

# APPENDIX 10

# DATA FOR SUBJECTS' RESPONSES: DISTINCTIVE FEATURES

## DATA FOR DISTINCTIVE FEATURE RESPONSES
(For all subjects, by subject number)

| | Subject Descriptions | | | | | |
|---|---|---|---|---|---|---|
| Phoneme | Strong | Weak | Short | Long | Changing | Non-Changing |
| o | 123456 | | | 123456 | | 123456 |
| u | 123456 | | | 123456 | | 123456 |
| ɔ | 123456 | | | 123456 | | 123456 |
| ɑ | 123456 | | | 123456 | | 123456 |
| e | 123456 | | | 123456 | 12456 | 3 |
| i | 123456 | | | 123456 | 123456 | |
| ʊ | 123456 | | 123456 | | | 123456 |
| ʌ | 123456 | | 123456 | | | 123456 |
| æ | 15 | 2346 | 1 | 23456 | 23456 | 1 |
| ɛ | 123456 | | 123456 | | | 123456 |
| ɪ | 123456 | | 123456 | | | 123456 |
| aɪ | 123456 | | | 123456 | 123456 | |
| au | 123456 | | | 123456 | 245 | 136 |
| ɔɪ | 123456 | | | 123456 | 123456 | |
| w | 123456 | | 123456 | | | 123456 |
| j | | 123456 | 123456 | | | 123456 |
| h | | | | | | |
| l | 123456 | | | 123456 | 123456 | |
| ɝ | 123456 | | | 123456 | 1256 | 34 |
| m | | 123456 | | 123456 | | 123456 |
| n | | 123456 | | 123456 | | 123456 |
| ŋ | 123456 | | | 123456 | 123456 | |
| v | | 123456 | 123456 | | | 123456 |
| z | | 123456 | | 123456 | 123456 | |
| ð | | 123456 | | 123456 | 123456 | |
| ʒ | | 123456 | | 123456 | | 123456 |
| f | | | | | | |
| ʃ | | | | | | |
| b | | 123456 | 123456 | | | 123456 |
| d | | 123456 | 123456 | | | 123456 |
| dʒ | | 123456 | 123456 | | 256 | 134 |
| g | | 123456 | 123456 | | | 123456 |
| p | | 123456 | 123456 | | | 123456 |
| t | | 123456 | 123456 | | | 123456 |
| tʃ | | 123456 | | 123456 | 123456 | |
| k | | 123456 | 123456 | | | 123456 |

# APPENDIX 11

# SUBJECT RESPONSES FOR PHONEMES BY PAIRED COMPARISONS

SUBJECT RESPONSES FOR PHONEMES BY PAIRED COMPARISONS
(Different phonemes with identical distinctive features)

| Phoneme pairs | Described as "same" (2 trials, 6 subjects) | Described as "different" (2 trials, 6 subjects) | Mixed responses |
|---|---|---|---|
| b-d | 123456 | | |
| aɪ-ɔɪ | 123456 | | |
| ɛ-ʊ | 123456 | | |
| ð-z | 123456 | | |
| ʊ-ʌ | 123456 | | |
| ɛ-ɪ | 123456 | | |
| ɔ-a | 13456 | 2 | |
| e-aɪ | 12346 | 5 | |
| i-ŋ | 13456 | 2 | |
| g-b | 13456 | 2 | |
| ʒ-m | 12456 | 3 | |
| k-t | 13456 | 2 | |
| o-ɔɪ | 12356 | | 4 |
| ɔɪ-aɪ | 12356 | | 4 |
| v-j | 13456 | 2 | |
| d-g | 12356 | 4 | |
| l-i | 1356 | 24 | |
| ʒ-n | 1256 | 4 | 3 |
| i-aɪ | 1236 | 5 | 4 |
| l-e | 1235 | 6 | 4 |
| b-v | 1234 | | 56 |
| b-j | 1356 | 2 | 4 |
| d-v | 1245 | 6 | 3 |
| k-b | 1456 | 3 | 2 |
| aɪ-o | 156 | 23 | 4 |
| e-i | 146 | | 235 |
| k-d | 345 | 16 | 2 |
| l-aɪ | 136 | 2 | 45 |
| ɛ-w | 245 | 136 | |
| v-g | 235 | 46 | 1 |
| l-ŋ | 234 | 156 | |
| t-b | 135 | 246 | |
| ŋ-e | 245 | 136 | |
| ŋ-aɪ | 235 | 146 | |
| oɪ-i | 23 | 1456 | |
| g-k | 36 | 24 | 15 |
| ŋ-ɔɪ | 24 | 1356 | |
| o-u | 36 | 14 | 25 |
| w-ʊ | 24 | 156 | 3 |
| a-u | 13 | 56 | 24 |

(continued)

Different phonemes with identical distinctive features.

| Phoneme pairs | "same" | "different" | Mixed responses |
|---|---|---|---|
| g-t | 46 | 15 | 23 |
| o-e | 13 | 2456 | |
| j-d | 25 | 1346 | |
| o-i | 34 | 1256 | |
| w-ε | 1 | 23456 | |
| v-p | 6 | 12345 | |
| p-k | 6 | 12345 | |
| v-k | 6 | 125 | 34 |
| l-ɔɪ | 4 | 1356 | 2 |
| ð-tʃ | 4 | 12356 | |
| t-p | 3 | 1456 | 2 |
| t-j | | 12456 | 3 |
| o-l | | 1456 | 23 |
| j-g | | 12456 | 3 |
| p-b | | 13456 | 2 |
| p-d | | 13456 | 2 |
| ŋ-o | | 123456 | |
| w-ʌ | | 123456 | |
| p-g | | 123456 | |
| z-tʃ | | 123456 | |
| j-p | | 123456 | |
| j-k | | 123456 | |
| v-t | | 123456 | |

(Phonemes differing in one or more dimensions)

| Phoneme pairs | "same" | "different" | Mixed responses |
|---|---|---|---|
| z-e | | 123456 | |
| ɑ-n | | 123456 | |
| u-ʊ | 13456 | | 2 |
| v-n | | 123456 | |
| ɔ-ε | | 123456 | |
| i-ɪ | | 123456 | |
| n-z | | 13456 | 2 |
| e-ɔ | | 123456 | |
| n-ɪ | | 123456 | |
| ɔɪ-I | | 123456 | |
| tʃ-t | | 123456 | |
| ɪ-tʃ | | 123456 | |

(continued)

(Phonemes not described consistently by distinctive features.)

| Phoneme pairs | "same" | "different" | Mixed responses |
|---|---|---|---|
| g-dʒ | 12356 | 4 | |
| b-dʒ | 1345 | 26 | |
| j-dʒ | 1234 | 6 | 5 |
| k-dʒ | 1346 | 25 | |
| dʒ-d | 3456 | 1 | 2 |
| æ-o | 1346 | 5 | 2 |
| dʒ-ʊ | 2346 | | 15 |
| æ-l | 123 | 46 | 5 |
| aɪ-æ | 126 | 35 | 4 |
| ɔɪ-æ | 136 | 245 | |
| dʒ-k | 36 | 24 | 15 |
| ŋ-æ | 35 | 146 | 2 |
| t-dʒ | 4 | 256 | 13 |
| ɛ-ɝ | 5 | 123456 | |
| æ-z | | 12345 | 6 |
| ɝ-ʊ | | 13456 | 2 |
| dʒ-au | | 123456 | |
| ð-æ | | 123456 | |
| ɝ-ɪ | | 123456 | |
| ɝ-ʌ | | 123456 | |
| p-dʒ | | 123456 | |
| ɝ-w | | 123456 | |

# APPENDIX 12

# SUBJECT RESPONSES FOR IDENTICAL PHONEMES IN PAIRS

SUBJECT RESPONSES FOR IDENTICAL PHONEMES IN PAIRS

| Phonemes* | Described as "same" (2 trials, 6 subjects) | Described as "different" (2 trials, 6 subjects) | Mixed responses |
|---|---|---|---|
| u-u | 123456 | | |
| e-e | 123456 | | |
| ʊ-ʊ | 123456 | | |
| ʌ-ʌ | 123456 | | |
| ɛ-ɛ | 12456 | | 3 |
| ɔɪ-ɔɪ | 123456 | | |
| v-v | 123456 | | |
| ɔ-ɔ | 123456 | | |
| ɝ-ɝ | 123456 | | |
| p-p | 123456 | | |
| b-b | 123456 | | |
| z-z | 123456 | | |
| v-v | 123456 | | |
| m-m | 123456 | | |
| g-g | 123456 | | |
| ʒ-ʒ | 123456 | | |
| dʒ-dʒ | 123456 | | |
| ŋ-ŋ | 123456 | | |
| l-l | 123456 | | |
| æ-æ | 123456 | | |
| n-n | 123456 | | |
| æ-æ | 123456 | | |
| o-o | 12356 | | 4 |
| w-w | 123456 | | |
| g-g | 123456 | | |
| aɪ-aɪ | 123456 | | |
| au-au | 123456 | | |
| ð-ð | 123456 | | |
| t-t | 123456 | | |
| j-j | 123456 | | |
| d-d | 123456 | | |
| tʃ-tʃ | 123456 | | |
| k-k | 123456 | | |
| i-i | 123456 | | |
| a-a | 123456 | | |
| i-i | 123456 | | |

* Three pairs are replicated: v, æ, i