THE EFFECT OF SPEAKER AND PRESSURE VARIATION ON THE VIBROTACTILE RECEPTION OF SELECTED SPOKEN ENGLISH PHONEMES

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JERRY MITCHELL HIGGINS

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This is to certify that the

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presented by

Jerry Mitchell Higgins

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ABSTRACT

THE EFFECT OF SPEAKER AND PRESSURE VARIATION ON THE VIBROTACTILE RECEPTION OF SELECTED SPOKEN ENGLISH PHONEMES

By

Jerry Mitchell Higgins

Four subjects responded to tape recordings of five English phonemes spoken by four General American speakers, i.e., an adult male, an adult female, a pre-adolescent male, and a pre-adolescent female. The experimental phonemes were selected from those used in a 1970 study by Haas. Each subject responded to each speaker under five conditions consisting of different levels of contactor pressure on the fingertip. The transmission system used a single, cantilever mounted transducer, the Clevite PZT-5B Bimorph.

Analysis of variance indicated that for four of the experimental phonemes, i.e., /u/, /ʌ/, /ɑ/, and /n/, there were no significant effects on phoneme threshold levels attributable to speaker variation, contactor pressure variation, sex of the receiver (subject), or interactions between any of the preceding factors. For the fifth phoneme, /b/, no significant effects were found for pressure or sex variations or any interactions, but a speaker effect was noted at the 0.05 level of significance. Examination indicated that the speaker effect was a threshold dichotomy between adults and children. The explanation for this dichotomy was not

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apparent; but it was noted that the phoneme /b/ was less stable than the others, particularly for the pre-adolescent female speaker. It was noted that the phoneme /b/ is a relatively weak sound, both in terms of speech power and tactile rank. It was hypothesized that, if the pre-adolescent female speaker should prove to be representative of the population of pre-adolescent female speakers, vibrotactile reception of the phoneme /b/ may not be of significant benefit as a supplement to visual reception of that phoneme. Although this would not be of critical importance for the highly visible /b/, it was suggested that the same pattern might be true of other phonemes not tested in this study.

Excellent agreement was noted among subjects' absolute threshold scores for all speakers at all pressure levels. Although no one pressure or pressure range stood out as being preferable insofar as objective analysis was concerned, subjective evaluations by the subjects indicated that 15 grams of contactor pressure on the fingertip, plus or minus 5 grams, was to be preferred.

Comparison of mean thresholds obtained by Haas and the present study showed a significantly high correlation. However, whereas Haas obtained a consistent slope in the thresholds recorded for the experimental phonemes, results of the present study had the three experimental vowels clustered together near the same threshold, with the consonants following a slope similar to that yielded by Haas' subjects. It was noted that means in the present study correlated even more

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more highly with the relative speech power levels of the phonemes than was so in Haas' study, although Haas found this correlation to be significant. Further, it was noted that thresholds for the phonemes were generally poorer in the present study than those obtained by Haas, with the exception of the threshold for /ɑ/.

Various possible explanations for the differences in slope and threshold shown by the two studies were discussed. Although it was not possible to state specifically the reason for the discrepancies, the most obvious potential cause to be investigated seemed to be possible differences in Bimorph responses to speech signals. It was pointed out that the Bimorph used by Haas was damaged subsequent to his study, and a different Bimorph of the same type was utilized in the present study.

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By

Jerry Mitchell Higgins

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New ways of expressing appreciation on the printed page are hard to come by. Nevertheless, many people have had a part, either directly or indirectly, in enabling me to do this study. To all of them, a special note of thanks is due.

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CHAPTER I

INTRODUCTION

Various investigators through the years have looked into the possibility of utilizing the cutaneous sensory receptors as an avenue of communication. An immediately apparent objective is to aid the deaf and profoundly hard-of-hearing in the understanding of speech, since those afflicted with the loss of a sensory modality are obviously handicapped and will benefit from more efficient use of their intact senses.

Aside from the physically handicapped, Bliss (1963) suggests that others would also benefit if it should somehow prove possible to use the cutaneous channel for efficient communication. For example, with some of today's complex equipment the visual and auditory channels of the operator may easily become overloaded; it would be advantageous to have other avenues of communication available. Today's aircraft are a case in point. Pilots must be visually alert to a myriad of dials and gauges and auditorily receptive to various radio transmissions. Additional visual or auditory input might be impractical, whereas tactile stimulation might still prove useful. Further, for military and other purposes, it is sometimes necessary for communications to be e

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surreptitious; it would be most helpful if a small tactile communication system could be concealed on the body and any transmitted messages could be felt rather than seen or heard.

In the 1920's it was thought that cutaneous speech reception could be used to circumvent totally the auditory system, and both mechanical vibrations and electrical impulses were used in experimental situations. Although limited success was achieved, investigators became increasingly more aware of difficulties to be overcome and the apparently inherent limitations of the cutaneous system, not the least of which is the skin's limited response within the critical speech range.

Research continues and basic data are being accumulated. Still, little is known. As Geldard (1969) says:

> We are . . . dealing with a tissue that is equipped with overlapping neural networks that must be relatively unlimited in their information-processing potentialities. And what do we . . . know about these possibilities? Precious little. For one and a third centuries . . . we have periodically tabulated and graphed two functions, the two-point limen and single-point localization. This, together with a modicum of very crude information concerning perception by graphesthesia and the recurring discovery that appreciation of form tactually is a practical impossibility in the absence of exploratory manipulations . . . constitute pretty much the full catalogue.

Gibson (1968) underscores the need for more information when he states:

> Major progress in cutaneous communication requires knowledge of perceptual properties of touch. The presently limited nature of cutaneous communication reflects the failure to make effective use of these properties, rather than reflecting any inherent

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> limitations of the touch sense. To find whether the cutaneous channels are effective for receiving more than simple, unidimensional warning information, or slow speech transliteration, it is essential to determine the perceptual properties of stimuli varied systematically along temporal and spatial dimensions.

Part of the difficulty in determining the cutaneous system's capability for the transmission of information has been due to the lack of adequately sophisticated vibratory devices. Continuing strides are being made in resolving this problem; but as Bliss (1963) states, "no device as yet has fully utilized all the informational capacity of the tactile and kinesthetic senses." This is as true today as it was when Bliss made the comment.

Attempts to transmit specific information by means of cutaneous stimulation have taken a number of different forms. Bliss (1963) suggests that they can be subdivided into those which depend on simple contact or pressure, those which use mechanical vibration, those which use electrical stimulation, and those which stimulate by use of an air jet.

Braille is an example of a communication medium which utilizes simple contact or pressure. Several machines have been developed which automatically transmit braille to the fingertip.

There have been various methods devised which utilize mechanical vibration. Gault, in the 1920's, attempted to apply speech energy directly to the skin. As was previously mentioned, whereas some limited success was achieved with versions of Gault's Teletactor, no practical communication

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system has as yet evolved, and it is now generally held that cutaneous receptivity cannot be used as a substitute for auditory receptivity. However, this does not rule out the possibility that it might serve as an effective supplement to whatever limited information might be received through a deficient auditory system. Although he has made very little specific information available, Guberina (1965) utilizes supplementary tactile information in his approach to aural rehabilitation, having his students grasp a device similar to a bone conduction receiver.

Part of the problem in attempting to interpret information transmitted by means of mechanical vibration is that the cutaneous system responds efficiently only to frequencies within a limited range, as has already been mentioned. Contemporary authorities disagree as to precisely what this range is, although many agree that efficient cutaneous response is limited to those frequencies at or below the lower end of the critical speech range. For example, Von Bekesy (1967) states that the range spans 50 to 500 Hz, whereas Kringlebotn (1968) would locate the upper limit at about 800 Hz. However, some research contradicts this. Russian studies have shown responses up to 2,000 Hz which have potential practical usefulness, according to Sokolyanskiy (1968).

In addition, it is difficult to distinguish between a change in intensity and a change in frequency. Some have sought to circumvent these problems by transposing the t

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speech frequencies to a lower range more compatible with cutaneous sensitivity. Others have used many small vibrators in such a way that the filtered but otherwise unaltered speech frequencies were mapped into spatial locations. Many variations on these types of themes have been developed and investigated, with varying degrees of success.

Other approaches have utilized other types of stimuli, including air jets and electricity. Researchers at the Massachussetts Institute of Technology have experimented with small air jets, as in handwriting on the skin. Cutaneous stimulation with electricity has been hampered by the small dynamic range between the threshold of feeling and the threshold of pain, with the consequent need to avoid pain presenting definite problems.

The preceding overview serves to underscore the fact that many means of utilizing the cutaneous channel as a system of information transmission are being investigated. As is apparent, even the optimum method of stimulating the somesthetic senses for information transmission has not yet been agreed upon. Once that has been discovered, the optimum procedure for coding the desired message remains to be determined. Bliss (1963) contends that "it will probably be necessary to develop more complex information-processing and coding methods in order to transform the message so that it is better matched to the channel and the human perceptual organization abilities." To this end, basic research is still essential. Therefore, investigators continue to in

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investigate the frequency and intensity ranges to which the skin will best respond. Further, contemporary researchers are seeking to determine the most sensitive physiological locus for the stimulator, the response of cutaneous receptors to multiple versus individual stimuli, the optimum size of the contactor, and other related areas. The investigations have encompassed both pure tones and speech. With more carefully controlled investigations, much more has been determined about tactile reception. Still, much remains to be learned.

Statement of Problem and Purpose of Study

In 1970, at Michigan State University, Haas sought "basic information relative to the functional utility of cutaneous reception of the speech code." Part of the basic information he obtained was the intensity level needed to reach vibrotactile absolute thresholds for each of the English phonemes. His results are contained in Appendix 1 of this study. In establishing these thresholds, Haas used one adult male General American speaker to provide the stimulus materials. As he pointed out in his final chapter, "it is clear that the future success of tactile reception of oral speech is contingent upon knowledge of the variability due to speaker effects." Therefore, the first goal of the present study will be to duplicate Haas' experimental situation and determine whether or not speaker variation affects the threshold level for phonemes.

Following the advice of Dr. Frank A. Geldard at the Princeton University Cutaneous Research Laboratory, Haas chose to utilize the piezoelectric ceramic Bimorph developed and made commercially available at the Clevite Corporation of Bedford, Ohio, as his tactile stimulus transmission system. The reasons he cited included the Bimorph's "simplicity of design, broad frequency response characteristics, almost instantaneous 'on-time' of transmitted signals, and excellent manageability for coupling with the skin." (See Appendix 2 for further information about the Bimorph.) At the advice of Dr. C. E. Sherrick, an associate of Geldard's, Haas elected to use a mechanical contactor pressure of 15 grams ($\pm$ 5 grams) beyond that point where the subject first indicated he could feel the tip of the contactor. However, as Haas pointed out, no literature speaks to "the effects of varying amounts of applied pressure when employing cantilever mounted vibrators." On the other hand, using other types of vibrators, Verillo (1966) has established the fact that increased contactor pressure results in decreased thresholds for pure tones. It is likely that this is true for speech stimuli also. Obviously, if vibrotactile stimulation is ever to be used for the transmission of oral speech, it is essential that information be available with regard to how the cutaneous threshold is affected by variations in contactor pressure. Further, a determination of the optimal range of pressure should be made. Therefore, the second goal of the present study will be to determine whether or not variation in contactor pressure influences the threshold level for phonemes, and which pressure or range of pressures is optimal.

Weinstein (1968) has established that, for pure tones, women demonstrated greater sensitivity to pressure than men. The third goal of the present study will be to determine whether or not the sex of the receiver (subject) affects the threshold level for phonemes.

Finally, it will be of interest to note whether or not there are any interactions resulting from the manipulation of the speaker-pressure, speaker-sex of subject, or pressure-sex of subject variables. This will be the fourth question in the present study.

To recapitulate, this study will seek to duplicate the basic experimental conditions of the Haas study. The exceptions will be the number of speakers and the number of contactor pressures used. Given the restrictions of the Haas experimental conditions, the purposes of the study will be to answer the following questions:

1. Does varying the speaker affect the threshold level for phonemes?
2. Does variation in contactor pressure influence the threshold level for phonemes?
3. Does the sex of the receiver (subject) affect the threshold level for phonemes?
4. Are there interactions attributable to manipulation of the speaker-pressure, speaker-sex of subject, or pressure-sex of subject variables?

As implied previously, in seeking answers to the above questions, it was decided to reproduce the conditions of that portion of the Haas study which related to the determination of vibrotactile thresholds. This decision specifically influenced the method of preparation of stimulus materials, the tactile stimulus transmission system used, and the methods employed in obtaining subject responses.

Importance of the Study

As has been pointed out, it is generally agreed that cutaneous stimulation cannot be expected to substitute for the auditory reception of ongoing speech. On the other hand, various sources do claim that the cutaneous channel can contribute significantly as a supplement to defective auditory reception. Assuming that this is true, it behooves one to discover those parameters of the cutaneous system which are of importance in the reception of speech signals. It seems apparent that the thresholds of phoneme reception would be among these important parameters. Likewise, it is clear that we need to know whether or not different speakers yield essentially the same results. It is to be expected that individual subjects would vary somewhat, for purely physiological reasons, but it would be of interest to discover whether or not one sex is more sensitive to vibrotactile stimulation with speech sounds than is the other.

It is recognized that different equipment and different techniques might yield different results. It is further recognized that the individual, isolated phoneme is an artificial entity insofar as ongoing speech is concerned. However, it is obvious that a beginning has to be made somewhere. Geldard (1969) quotes Helmholtz as stating that " . . . there is little hope that he who does not begin at the beginning of knowledge will ever arrive at its end." The present investigator feels that Haas' study began at the beginning and was a step in the right direction, and that building on it is a logical next step.

Definitions

In that this study is an outgrowth and replication of the basic conditions of the Haas study, the same definitions have been adopted, wherein they apply, and a definition for relative intensity levels has been added. The definitions are as follows:

Vibrotactile stimulation: 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. Geldard (Haas, 1970) stated that the Bimorph is the latest and most efficient transducer developed for purposes such as Haas' and this study. It has virtually no "on-time" lag and responds to frequencies above 20,000 Hz. Its basic construction is a two ceramic plate sandwich-type structure.

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. In this case, the signals are selected English phonemes presented by the psychophysical method of limits.

Psychophysical method of limits: Underwood (1966) 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.

For the purposes of Haas' research, each subject was given eight trials. Four of these trials were of the ascending order, and four of the descending order. His raw data for those phonemes selected to be used in the present study will by found in Appendix 3. For the purposes of the present research, each subject was given four trials, two each of the ascending and descending order.

Phonemes: Phonemes are the basic linguistic units which, when combined, comprise words and sentences. Taken individually, they do not symbolize any object or concept. However, in relation to other phonemes they distinguish one word from another (Denes and Pinson, 1964). Phonemes may be considered as speech sound families, with specific symbols (phonetic symbols) used to identify these families, with each symbol representing a group of "slightly varying sounds that includes all of the variations which are perceived acoustically as the sound under consideration" (Judson and Weaver, 1965).

Relative intensity levels: Fletcher (1953) established relative intensities for the various phonemes of English. Haas (1970) adjusted his experimental phonemes to conform to these intensities, plus or minus 2 dB. Likewise, the experimental phonemes recorded by the four speakers for the present study have been electronically adjusted to meet the same standards. Fletcher's criteria, and the results of both Haas' adjustments and those of the present investigator may be found in Appendix 4.

Organization of the Research Report

Chapter I has been organized to provide an introduction to the problem of the cutaneous reception of information. It includes a brief overview of the types of investigations which have been conducted by previous researchers, and cites some of the problems which have been encountered, as well as their implications for tactile speech reception. A statement of the purpose and importance of the investigation has been presented, together with definitions of terms used throughout the study.

Chapter II consists of a review of the literature related to the reception of vibratory speech stimuli by the cutaneous receptors.

Chapter III contains a description of the subjects, the equipment used, procedures employed, and statistical design followed in the study.

Chapter IV presents the results of the study with respect to the questions posed in Chapter I, together with a discussion of those results.

Chapter V consists of a summary statement, conclusions drawn from the results of the study, and the implications for further research.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

In his unpublished doctoral thesis, Haas (1970) has extensively documented the literature pertaining to investigations into the response of cutaneous receptors to pure tone and speech stimuli. Although this information is very interesting and informative, much of it is not immediately pertinent to the present study and will not be formally repeated here. However, it is appropriate to briefly summarize Haas' findings. For example, with regard to comparisons between auditory and tactile channels, he indicated that various investigations showed that:

1. Although there are many similarities between taction and audition, there are so many differences that taction cannot be considered as a substitute for audition.

2. The tactile modality has its counterparts for the auditory concepts of intensity, frequency, duration, traveling waves, localization, recruitment, and neural inhibition.

3. The information transmitted to the nervous system by the tactile modality, with regard to the aforementioned concepts, is "crudely molar compared to the sophisticated molecular capability of the human ear."

4. The limited capability of the skin to receive frequencies within the critical speech range is of primary significance.

Looking at variables influencing vibrotactile thresholds, Haas noted that:

1. Most researchers agree that the fingertips are the most sensitive to vibrotactile stimulation of the various body sites tested.

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

3. Multiple simultaneous vibrator stimulation results in masking effects causing significant threshold elevations.

4. Large contactors result in an inverse relationship between the vibrotactile threshold and the contactor area, yielding a U-shaped curve with maximum sensitivity at 250 Hz, whereas when the contactors are small the threshold curves are independent of frequency, i.e., flat.

5. The role of adaptation is unclear.

6. The phenomenon of recruitment is present, but the metrics are not known.

Haas further extensively documented research into the development and application of stimulus transmission systems; but since these systems have been used in attempts to transmit speech information, it is appropriate that they be dealt with more extensively in the pages that follow.

The same is true with respect to investigations into cutaneous sensory reception of the speech code.

History of Investigations into Cutaneous Speech Reception

Whereas different aspects of tactile sensitivity have been the subject of research for a number of years, investigation into the usefulness of the cutaneous system as a channel for the reception of the speech code grew out of Gault's work in the early 1920's. At first Gault considered the cutaneous channel to be equal to the auditory channel insofar as its potential to receive vibratory stimulation (Gault, 1934). His first experiment consisted of using a long speaking tube extended through several walls, with the subject seeking to discriminate between assorted tuning fork vibrations and speech sounds (Gault, 1924). His next investigation involved the use of a device similar to the earpiece of a telephone receiver. Again, tubes were used to transmit the speech signal from a room 35 feet away from the subject, with the subject seeking to discern the signal via his fingertips (Gault, 1926a).

In 1928 Gault was assisted in his research by the Bell Telephone Laboratories, which helped develop a piece of equipment called the Teletactor. This device divided the speech signal into five frequency bands, each of which was then amplified and introduced to a different finger of one hand by means of simple vibrators. Each vibrator passed only one portion of the filtered speech signal, with a total

range covered by all five vibrators of 0 to 2,600 Hz (Gault, 1928). Gault's first experiment with the Teletactor employed a 28 year old deaf female. After practicing for 200 hours, she was able to distinguish about 50 percent of a list of 172 monosyllabic words (Gault, 1924). In another instance, following only 28 half-hour training sessions, a subject was able to judge which of 10 brief stimulus sentences had been presented to him, with about 75 percent accuracy. However, it was reported that the results were significantly lowered with a change of speakers or a reduced rate of speaking (Gault, 1926b).

Gault also experimented with the concurrent use of touch and vision (Gault, 1926c), using vibrotactile stimulation to help deaf students develop a feel for the rhythms of speech and to identify various types of speech patterns by their movements. He claimed that hearing people did this auditorily to the point where the "movement" of spoken discourse provides cues which enable them to perceive its meaning, with rhythm, accent, and emphasis all making a contribution. He claimed that subjects could improve their understanding 40 to 100 percent over lipreading scores alone by combining taction with vision. He attributed this to the fact that taction helped the subjects get a feel of the rhythm of speech and provided help in perceiving words not easily distinguished by vision alone. His evidence suggested that, once trained, taction could be dispensed with and the benefits would still accrue.

Cloud (1933) reported on the use of Gault's Teletactor in an experiment using eight deaf children. He concluded that it aided in tone production, helped the subjects distinguish between long and short vowels, helped them recognize silent and unvoiced elements in words, enabled them more easily to discern and utilize the correct placement of accent in syllable combinations, aided in the correction of omitted or added voiced speech elements, and resulted in smoother speech on the part of those children who used the Teletactor, as contrasted with those in the same age bracket who did not.

Haas (1970) reported an experiment by Myers using a "Shake-Table," a single vibrator which stimulates the thumb and inner three fingers of the hand. Myers claimed an average of 91 percent accuracy in discriminating between 16 single words after 8 training sessions.

Another approach to vibrotactile stimulation has evolved as an attempt to circumvent the problems arising from the frequency range limitations of the cutaneous system. Equipment has been developed by various researchers which transposes the speech frequencies downward and transmits them over narrow low frequency bands. The first of these units was Dudley's Vocoder, developed in 1936 (Dudley, 1936). The Vocoder derives a small set of measure signals representative of energy fluctuations in a corresponding set of speech frequency bands. The measure signals are then transmitted over narrow low-frequency channels. At the receiver, the speech is approximately reconstructed by modulating the spectrum of a broad-band source in accordance with the frequency regions and amplitudes of the measure signals. Originally, this reconstructed signal was presented acoustically to the listener. Application of the Vocoder technique to tactual stimulation was first attempted by Levine and others at the Massachussetts Institute of Technology, using a device called FELIX (Pickett and Pickett, 1963). FELIX divides the speech spectrum into seven frequency bands, deriving an approximate measure of the energy in each band. These measures are then presented to the skin of the subject in the form of amplitude variations. Only a few preliminary trials were made with FELIX, according to Pickett and Pickett. They have reported that more recently Fant and his colleagues at the Speech Transmission Laboratory of the Royal Institute of Stockholm have developed a ten channel, two-hand type of Vocoder. This device utilizes bone-conduction transducers, presenting the lowest frequency to the little finger on the left hand and progressing to the higher frequencies on the right hand. In the same article, Pickett and Pickett reported on using the ten-channel Vocoder in an experiment looking at the ability of subjects to discriminate between various vowel pairs and consonant pairs. They found results varying across the spectrum from fair success, through moderate, good, and consistent success for various vowel pairs, with vowel sounds of relatively greater duration yielding more consistent results. Looking at consonant pairs, the results ranged from 22 percent to 99.5 percent discrimination. One of the problems they noted was the masking effect which results from using multiple vibrators. Further, they commented on the fact that a ten-channel vibrating mechanism is cumbersome, suggesting that the maximum number which can be used profitably might be three or four discrete loci.

Kringlebotn (1968) experimented with a five-vibrator tactual vocoder called Tactus. With it, he states:

> the speech signal . . . is divided down into the frequency range for tactual vibration by the successive multi-vibrator circuits. One [bone conduction] vibrator for each of five frequency ranges in the original speech thus provides a spatial pattern of vibrations to represent the speech frequency patterns.

With this system, the pulse signal excites the first vibrator and then is divided down successively for the remaining vibrators with pulse signals having frequencies one-half, one-fourth, one-eighth, and one-sixteenth of the original frequencies. Using deaf children as subjects and closed choice experiments of limited complexity, Kringlebotn concluded that the apparatus showed promise: (1) as a supplement to lipreading under teaching conditions, (2) as an aid for the learning of lipreading, (3) as an aid in speech teaching and correction, and (4) as a rhythm indicator.

Keidel (1958) experimented with storing speech signals on magnetic tape, recorded at a rate of 15 inches per second, and then transposing the frequencies downward by manipulating the playback speed. The resultant speech signals were then fed into a mechanical vibrator based on a model developed by Bekesy in 1955 to further his study of the traveling wave theory. The model consisted of a plastic tube case around a brass tube with a slit in it. The tube complex, which was attached to the skin of the forearm, was filled with fluid and a vibrating piston within the tube set the fluid in motion. The result was that waves were produced which traveled from hand to elbow. Keidel describes his adaptation of Von Bekesy's model as follows:

> 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.

Keidel (1968) was pleased with the results, reporting that he was able to train subjects to recognize three types of monosyllabic words, the three types differing with regards to their frequency range.

In his doctoral dissertation, Johnson (1963) devised a system consisting of four loudspeakers, each two inches in diameter, which directly contacted the forearm of the subject, with speech signals transmitted through the speakers. On the face of each speaker a fabric was attached. The speech signal vibrations activated the center of the fabric, producing an elliptical vibratory pattern on the forearm. With training, Johnson indicated that lipreading scores of experimental subjects were enhanced when this system was used. This, and the previously cited study by Kringlebotn using the Tactus vocoder, are in agreement as to the positive effect tactile stimulation can have on lipreading. As mentioned earlier, Gault also felt that lipreading scores could be improved by supplementing vision with taction. He supported his conclusions with evidence obtained in several studies (Gault, 1930a, 1927, 1930b). Also, using the Teletactor and lipreading combination, Ilieva (1934) reported an increment in correct responses as compared with the score obtained by vision alone.

Geldard (1961), citing the various limitations of the cutaneous system and the problems inherent in trying to input ongoing speech, suggested that the best solution was to recode speech stimuli. Accordingly, he utilized the dimensions of locus, duration, and intensity to transpose language symbols into patterns over ten loci on the skin. This technique does not use speech sounds, per se, but patterns each letter of the alphabet, utilizing a 60 Hz sinusoidal signal as the primary stimulus, varying its intensity and duration. Geldard called his system the "vibratese language," and used the Bimorph as his vibrator. He claimed that his subjects had received up to 38 words per minute using this system.

As was mentioned in Chapter I, electrocutaneous research has been attempted, as well. Geldard (1960) has indicated, however, that no practical system has been developed to circumvent the problem of pain induced by electrical stimulation.

Research Specifically Pertinent to This Study

Of major significance to the present investigation, in that this study is a direct outgrowth of it, is Haas' investigation into the vibrotactile absolute thresholds of English phonemes. Haas (1970) states that:

> 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 fingertip.
>
> 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 (Haas, 1970).

The graphic illustration of Haas' rankings of the phonemes by detectability thresholds is found in Appendix 1.

Haas found that there was close agreement among the subjects' threshold scores, with closer agreement for consonant than for vowel sounds. Further, individual subject test-retest reliability was found to be excellent. In addition, he found that there was a strong relationship between the vibrotactile thresholds for spoken phonemes and the relative speech powers of the phonemes. Again, this relationship was more consistent for the consonant than the vowel sounds.

Verillo (1966), in his research into the effects of varying pressure on cutaneous sensitivity, established that thresholds for pure tone stimuli decrease in direct proportion to the extent of protrusion by the contactor. Verillo's findings supported earlier findings by Cohen and Lindley (1938) and Babkin, Rozen, Tumarkina, and Chernyak (1961).

Weinstein (1968), investigating various vibrotactile parameters for pure tones, established that women demonstrated greater sensitivity to pressure than did men.

In summary, with respect to research directly bearing on the questions posed by this study, Haas (1970) established vibrotactile thresholds for spoken English phonemes using one adult male General American speaker, Verillo (1966) demonstrated that vibrotactile thresholds for pure tones improve with increased protrusion of the contactor into the skin's surface, and Weinstein (1968) found that, for pure tones, women displayed greater sensitivity to pressure than men.

CHAPTER III

SUBJECTS, MATERIALS, EQUIPMENT, AND PROCEDURES

Four subjects were presented twenty experimental programs. The first four programs consisted of the determination of intensity required for absolute detection thresholds of selected English phonemes for four separate speakers at a specified amount of applied contactor pressure. The second, third, fourth, and fifth sets of four programs were identical to the first set of four programs and to each other, with the single exception that the specified amount of applied contactor pressure varied for each set.

Subjects

The four subjects, two males and two females, were between the ages of 24 and 30 years. None had known pathological conditions of the skin or central nervous system. All were either professionals or doctoral candidates in the field of Speech Pathology and Audiology.

It was determined that more subjects were unneccessary, since Haas (1970) established that there was good agreement between subjects with respect to cutaneous thresholds for phonemes.

Prior to each experimental session the four subjects were given a practice session, using the reference phoneme /ɔ/, with all conditions identical to those to be employed in the experiment. This practice session was used to reacquaint the subjects with the nature of the stimuli and the task.

Materials

Four taped programs of recorded English phonemes comprised the stimulus materials for the study. The magnetic recording tapes were Scotch brand, type 201. The phonemes employed were selected from those used by Haas, on the basis of mean threshold intensity. Haas' results may be examined in Appendix 1. Wherever a cluster of phonemes evidenced the same mean threshold intensity, randomization was used to select one phoneme as representative of each cluster. On the other hand, if a phoneme stood alone, i.e., was not clustered with others with regard to mean threshold intensity, that phoneme was automatically selected. By this means the phonemes /u/, /I/, /ɛ/, /ʌ/, /w/, /aʊ/, /ɑ/, /v/, /n/, /g/, /dʒ/, /b/, /t/, /ʒ/, and /h/ were isolated. Next, in the interest of time required of the subjects under fatiguing experimental conditions, the preceding list was reduced to six phonemes. Again, Haas' mean threshold intensities were the reference and, using the criterion of at least a 3 dB span between adjacent phonemes, the experimental phonemes /u/, /ʌ/, /ɑ/, /n/, /b/, and /h/ were selected. These phonemes ranged along the continuum from Haas' best to his poorest obtained mean threshold intensities.

The preceding phonemes, together with the reference phoneme /ɔ/, were recorded in the indicated sequence, yielding the four master tapes. These tapes consisted of the reference phoneme and each of the stimulus phonemes being spoken five or more times by each of the four General American speakers, i.e., an adult male, an adult female, a preadolescent male, and a pre-adolescent female. Each speaker was seated in a double-walled, sound-treated, prefabricated room. The microphone was placed approximately six inches from his lips at about a 45 degree angle. Recording procedures of Black (1949, 1952) and Fletcher (1953) were followed to obtain the best possible stress, duration, and natural speech power. Each speaker was informed that he would be told the phoneme to be recorded as it was required. Upon being signalled to begin, he was to say the indicated phoneme as naturally as possible, over and over again until he was signalled to stop, taking a breath between each utterance. The VU meter on the tape recorder was adjusted to 0 for the reference phoneme /ɔ/, which was always the first phoneme to be recorded, for each speaker in turn. Thereafter, no further adjustments were made.

Using the master tapes resulting from the foregoing procedures, the phonemes were dubbed onto an experimental tape and the best two utterances of each, as determined subjectively by the experimenter, were spliced into a new sequence determined by the table of random numbers. The sequence for each speaker was separately randomized.

The resulting taped stimuli were played for critical review by three speech pathologists familiar with phonetic symbols. They were seated in a double-walled, sound treated, prefabricated room, and the tapes were played through the speech circuit of a Maico MA-24 audiometer. They were asked to record, in appropriate phonetic symbols, whatever sounds they heard. Their responses were analyzed, and if at least one of each of the recorded phonemes for each speaker did not elicit 100 percent agreement among the speech pathologists, a second recording session was scheduled and additional utterances of the deficient phonemes were recorded. Again, the phonemes were submitted to evaluation by three speech pathologists and the results were analyzed. At this point, each speaker had produced at least one utterance of each of the selected phonemes which elicited 100 percent agreement by the speech pathologists. In those instances where more than one utterance for a given phoneme and a given speaker resulted in 100 percent agreement, an arbitrary choice was made between the two, thus narrowing the stimulus phonemes to be used in the study to one utterance of each phoneme per speaker. These phonemes were then spliced back into the original sequence and four experimental tapes were prepared, each containing eight consecutive repetitions of each phoneme, for a total of fifty-six stimulus events per speaker, including the /ɔ/. Each repetition was a replication of the original, single utterance previously selected.

As the repetitions were taped, the relative intensities of the experimental phonemes were adjusted to meet the relative speech power dimensions as specified by Fletcher (1953). The strongest speech sound /ɔ/, for example, is specified by Fletcher as being 28 dB stronger than the weakest sound /θ/. A level recorder (Bruel and Kjaer 2305) had been used to measure the relative intensities of the phonemes on the preliminary recordings. Comparing them to the values suggested by Fletcher, the amount of adjustment was determined and the peak values were equated at the time of preparation of the experimental tapes, as just mentioned, to the desired relative intensities, plus or minus 2 dB. The experimenter was fully aware of the fact that Fletcher's criteria were established using adults as subjects and therefore did not necessarily hold true for children. However, the arbitrary decision was made to apply the criteria to all four speakers, adults and children alike, in order to control for individual speech power differences among speakers. Haas (1970) had already established that there was a strong positive relationship between phoneme thresholds and relative speech power. Therefore, if this is the sole variable active in determining vibrotactile thresholds for spoken phonemes, it could be expected that the present study would yield no significant differences due to speaker effect. On the other hand, by controlling for the speech power variable, information might be obtained as to whether or not there might be other variables, peculiar to the individual speaker, which might be contributing factors in determining vibrotactile thresholds.

The resulting experimental tapes were replayed through the level recorder for a final check of relative intensities. (See Appendix 4 for a description of the relative intensity differences between the experimental phonemes and the stimulus phoneme, as specified by Fletcher, and as obtained by Haas and the present experimenter.)

The intensity of the reference phoneme /ɔ/, which Fletcher indicated was the phoneme with the highest intensity value, was used to determine the intensity level for the calibration tone. One minute of a 1,000 Hz sinusoidal tone was recorded at this level at the beginning of each experimental tape.

An inter-stimulus interval of two seconds was left between each of the eight consecutive replications of each phoneme, and an inter-phoneme interval of six seconds was left between each set of eight phoneme replications.

Noise spikes of approximately 15 dB were observed on the level recorder output. It was determined that these were the result of the activation of the on-off switch of the tape recorder. Although these were not audible through the earphones, they were spliced out as a safeguard against the possibility of their affecting tactile thresholds.

A subject threshold data form was prepared for use during the experiments. (See Appendix 7.)

Equipment

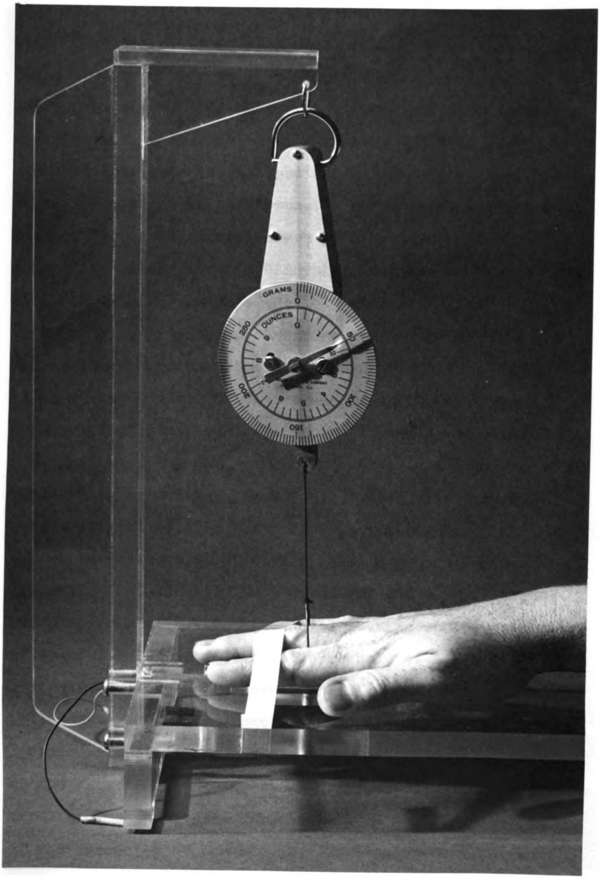
The following list constitutes the major instrumentation employed for this study:

Tape Recorder I (Ampex AG 440B-4)
Tape Recorder II (Ampex AG 600)
Tape Recorder III (Viking 433)
Microphone (Electrovoice 635A)
Level Recorder (Bruel and Kjaer 2305)
Audio Oscillator (Central Scientific Company)
Commercial Test Room (Industrial Acoustic Company, Inc., double walled room, Model 10-1052)
Audiometer (Maico MA-24) with Electrovoice SP-12 speaker
Tactile Stimulus Transmission System with piezoelectric ceramic Bimorph (Clevite Corporation)

Procedures

All experimental sessions were conducted in a double walled, sound treated, prefabricated room. For each experiment each subject was seated beside a table with his right arm resting on a foam rubber pad the same height as the platform housing the Bimorph. The right hand, palm down, was placed on the handrest platform and the middle finger was placed in the finger cradle with the fingertip extended over the Lucite rod contactor, coupling 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 then elevated to remove coupling with the contactor, and then lowered to the point where the subject just began to detect contact. Next, the finger cradle was lowered an additional number of grams dictated by the experiment being conducted.

To insure against any perceived auditory signals


GRAMS
OUNCES

emanating from the Bimorph, all experiments were conducted with 80 dB SPL of broad band white noise projected into the sound field from the speaker in the test room via channel two of the Maico MA-24 audiometer. This level of masking was the same as that selected by Haas in that it is the standard level used by Geldard and Sherrick for experiments using the Bimorph at the Princeton Laboratory. Further, Haas conducted a sound pressure level analysis of the speech sounds emanating from the Bimorph, obtaining a maximum level of 54 dB SPL for the /ɔ/, the loudest sound.

Prior to the experiments the Maico MA-24 audiometer was calibrated to the Bimorph by obtaining voltage measurements across the electrical terminals to the transducer. Inspection of the results in Appendix 8 will reveal that at a 40 dB attenuator dial setting on the audiometer, the voltage reading across the Bimorph was 1.6 volts. This level was arbitrarily chosen as the zero reference level for reporting the results of this study. Hence, a tactile threshold of 0 dB would be indicative of 1.6 volts across the Bimorph and an attenuator dial setting on the audiometer of 40 dB. Likewise, a tactile threshold of 10 dB would be indicative of 5.0 volts across the Bimorph and an attenuator dial setting on the audiometer of 50 dB.

All stimulus materials were amplified and attenuated by the Maico MA-24 audiometer and transmitted via the speech circuit of channel one, which permitted one dB adjustments of the intensity of the signal. The equipment range was

120 dB, which theoretically permitted 80 dB of amplification above the 40 dB dial setting of the audiometer which represented tactile zero. However, due to the nature of the test materials and limited applied voltage tolerance of the Bimorph, a range of only 40 dB, i.e., 40 to 80 dB on the attenuator dial of the audiometer, was utilized.

The order in which the five experimental pressure levels were presented was the same for each of the four subjects. It was arbitrarily decided to begin with 15 grams in order to have the "easier" threshold judgments first, to be followed by what might prove to be more difficult judgments. At any rate, based on Haas' results, it was known that thresholds could be elicited at 15 grams, whereas it was hypothesized that more pressure might result in damping effects and less pressure might result in an inability to discern vibrations sufficiently to establish consistent thresholds.

Experiment I. The purpose of this experiment was to determine the intensities required to elicit detection thresholds for the selected phonemes, for each of the four experimental speakers, with 15 grams of contactor pressure beyond that point where the subject first detected contact. The order of speaker presentation to the subjects was randomized (see Appendix 9).

Prior to each experimental session, the subject was presented with the following written instructions:

The purpose of this session is to determine what intensity is required in order for you to determine the presence of a tactile sensation at a given pressure setting. Each stimulus event represents an English phoneme. We are interested in absolute detection thresholds. Please respond on every occasion that you detect a vibration on your fingertip. Respond by briefly pressing the button provided.

Most of the stimuli will be presented around your threshold. As a result, 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. There will be one practice phoneme followed by six experimental phonemes for each of four speakers. A masking noise will be introduced into the test suite during threshold testing. Between phonemes, and between speakers while the stimulus tapes are being changed, the masking noise will be discontinued. This will indicate to you that we have completed the threshold series for a phoneme, and for a speaker, respectively. When the masking noise is re-introduced the presentation of the next phoneme will begin. Remember that the first stimulus for each phoneme will be strong.

Since the pressure contact of the Bimorph "needle" is one of the variables being investigated, you are asked to maintain the position of your right hand in the cradle throughout the test session. The session will last approximately one hour.

Before presenting the practice phoneme, the calibration tone was used to adjust the output gain of the Maico MA-24 audiometer to zero on the VU meter. This step was repeated for each of the four speakers. The practice session utilized the reference phoneme /ɔ/, with all conditions identical to those employed in the experiment itself.

Following the practice session, the psychophysical method of limits was used to elicit the detection thresholds of the six experimental phonemes. For all subjects, with each phoneme, there were two ascending and two descending series of stimuli, with an ascending series presented first, followed by a descending series, etc. Prior to the first ascending series the alerting signal, utilizing the experimental phoneme, was presented at the maximum intensity employed in the experiment (i.e., 40 dB re the calibration tone at 1.6 volts, which corresponded to 80 dB on the attenuator dial). This was followed by a stimulus of very low magnitude which was progressively increased until detected. The intensity at this point of detection was recorded as the threshold for that first ascending series. The signal was further augmented by 1 dB steps and responses were noted for three additional trials, at which time the process was reversed and the descending series was begun, reducing the stimulus by 1 dB steps until it was no longer detected, recording the last detected signal as threshold for that series. Attenuation was then continued for three additional trials, at which time the second ascension was initiated, to be followed by the second descension in turn. The average score for the four series was recorded as the absolute detection threshold for that given phoneme.

The subject was instructed to respond by pressing a signal button.

Phoneme presentation order was determined randomly.

Experiment II. The purpose of this experiment was to determine the intensities required to elicit detection thresholds for the selected phonemes, for each of the four experimental speakers, with 20 grams of contactor pressure beyond that point where the subject first detected contact. The order of speaker presentation to the subjects was randomized (see Appendix 9).

General procedures followed were the same as for Experiment I.

Experiment III. The purpose of this experiment was to determine the intensities required to elicit detection thresholds for the selected phonemes, for each of the four experimental speakers, with 10 grams of contactor pressure beyond that point where the subject first detected contact. The order of speaker presentation to the subjects was randomized (see Appendix 9).

General procedures followed were the same as for Experiment I.

Experiment IV. The purpose of this experiment was to determine the intensities required to elicit detection thresholds for the selected phonemes, for each of the four experimental speakers, with 25 grams of contactor pressure beyond that point where the subject first detected contact. The order of speaker presentation to the subjects was randomized (see Appendix 9).

General procedures followed were the same as for Experiment I.

Experiment V. The purpose of this experiment was to determine the intensities required to elicit detection thresholds for the selected phonemes, for each of the four experimental speakers, with 5 grams of contactor pressure beyond that point where the subject first detected contact. The order of speaker presentation to the subjects was randomized (see Appendix 9).

General procedures followed were the same as for Experiment I.

CHAPTER IV

RESULTS AND DISCUSSION

This chapter contains the basic data obtained and discussions of their significance with regard to the four experimental questions posed in this study, as follows:

1. Does varying the speaker affect the threshold level for phonemes?

2. Does variation in contactor pressure influence the threshold level for phonemes?

3. Does the sex of the receiver (subject) affect the threshold level for phonemes?

4. Are there interactions attributable to manipulation of the speaker-pressure, speaker-sex of subject, or pressure-sex of subject variables?

Analysis of variance was accomplished with a three-factor design with repeated measure (Winer, 1962).

In addition, agreement among subjects' absolute thresholds was investigated. Each subject's responses to the six selected phonemes were ranked and comparisons were accomplished, for each pressure separately, using the non-parametric Coefficient of Concordance (Kendall's W) (Downie & Heath, 1965).

Finally, the mean thresholds in the current study, for the adult male speaker with 15 grams of contactor pressure beyond the point where the subject first began to detect contact, were compared with those obtained by Haas (1970). The statistical procedure used was the Spearman-R Rank Correlation for the two sets of ranks (Siegel, 1950).

It will be noted that whereas six experimental phonemes were chosen to be used in this study, only five of the six appear in the figures and tables illustrating the results. The missing phoneme is /h/. The reason for its omission is the fact that no subject responded to this phoneme at any pressure, for any speaker, in the present study. Discussion of this phenomenon will by presented in the appropriate section of this chapter.

Effects of Speaker, Contactor Pressure, and Sex of Receiver

Each phoneme was analyzed separately by a three-factor analysis of variance design with repeated measures in order to determine whether or not there were any significant threshold deviations resulting from the experimental conditions. Factors included speaker, pressure, and sex of the receiver. Possible interactions of these factors were also investigated.

Phoneme /u/. At each of five experimental sessions each of four subjects was stimulated with the vibrotactile form of the phoneme /u/ spoken by each of four different speakers. The experimental sessions differed only in terms of the amount of pressure presented to the subject's fingertip by the Bimorph's contactor rod. Two ascending and two descending thresholds were established, the mean of the four comprising each subject's absolute threshold.

Figures 2 and 3 present the absolute threshold results in the form of histograms. Table 1 presents the statistical data obtained by analysis of variance. There were no significant effects attributable to any of the three variables or to interactions among them.

Table 1. Phoneme /u/. Analysis of Variance: Threshold Data

Source	d/f	Sums of Squares	Mean Squares	F-Ratio
P	4	95.398	23.849	0.162
PSx	4	76.470	19.117	0.130
P(I/Sx)	8	1173.622	146.702	
Sp	3	67.058	22.352	0.528
SpSx	3	76.786	25.595	0.605
Sp(I/Sx)	6	253.646	42.274	
Sx	1	3.570	3.570	0.005
I/Sx	2	1235.577	617.788	
PSp	12	59.841	4.986	0.346
PSpSx	12	58.947	4.912	0.340
PSp(I/Sx)	24	345.723	14.405	

P: pressure
Sp: speaker
Sx: sex of receiver (subject)
I/Sx: individual subjects within sex
4.760 required for significance at the 0.05 level of confidence

Phoneme /ʌ/. At each of five experimental sessions each of four subjects was stimulated with the vibrotactile form of the phoneme /ʌ/ spoken by each of four different speakers. The experimental sessions differed only in terms of the amount of pressure presented to the subject's fingertip by the Bimorph's contactor rod. Two ascending and two

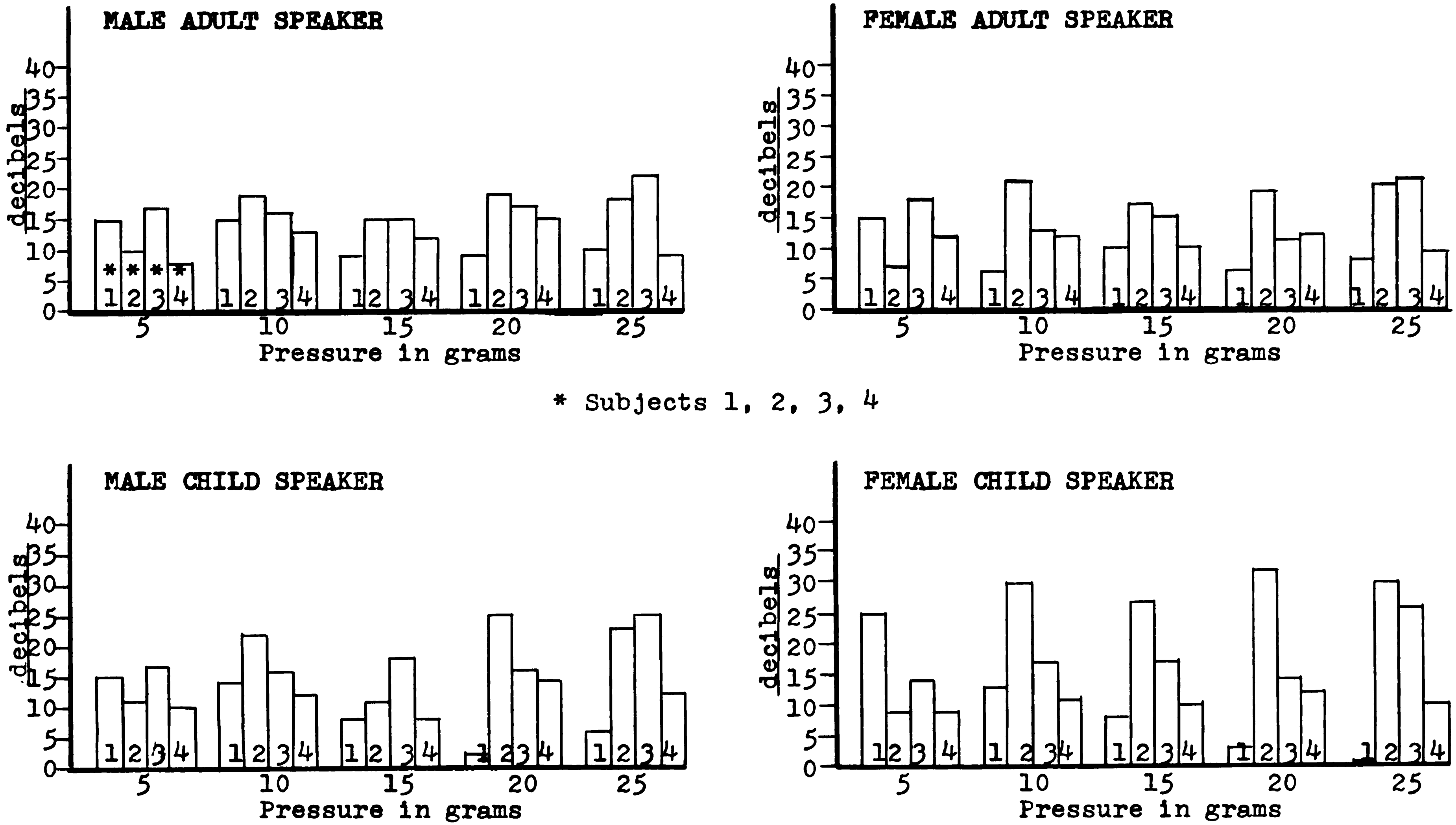


Figure 2. Phoneme /u/. Each Speaker Versus All Subjects at All Pressures
(0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

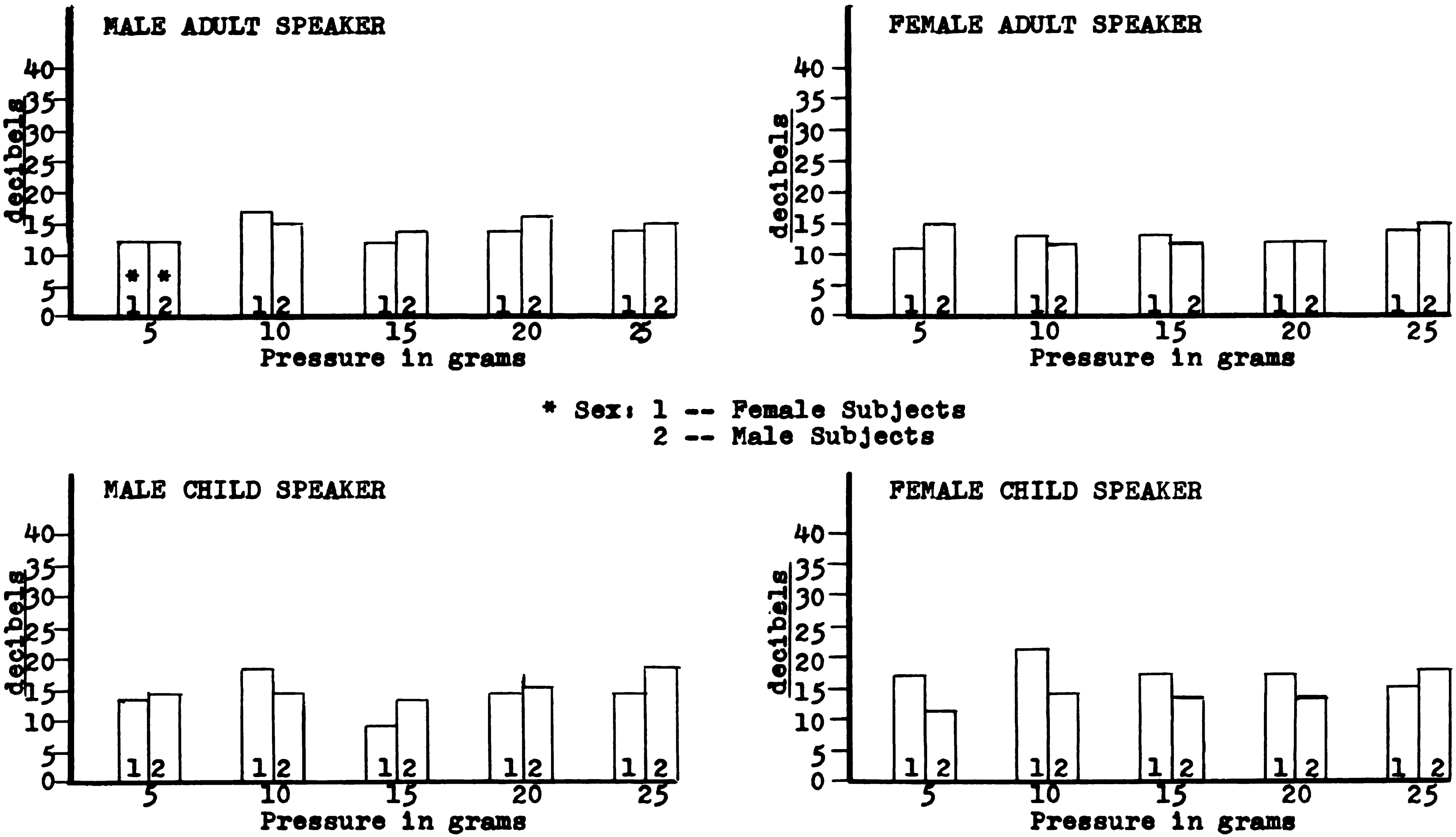


Figure 3. Phoneme /u/. Each Speaker Versus Both Sexes at All Pressures
(0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

descending thresholds were established, the mean of the four comprising each subject's absolute threshold.

Figures 4 and 5 present the absolute threshold results in the form of histograms. Table 2 presents the statistical data obtained by analysis of variance. There were no significant effects attributable to any of the three variables or to interactions among them.

Table 2. Phoneme /ʌ/. Analysis of Variance: Threshold Data

Source	d/f	Sums of Squares	Mean Squares	F-Ratio
P	4	73.581	18.395	0.135
PSx	4	89.974	22.493	0.166
P(I/Sx)	8	1082.752	135.344	
Sp	3	79.756	26.585	1.042
SpSx	3	35.106	11.702	0.458
Sp(I/Sx)	6	152.973	25.495	
Sx	1	0.180	0.180	0.00041
I/Sx	2	877.267	438.633	
PSp	12	43.443	3.620	0.250
PSpSx	12	43.650	3.637	0.251
PSp(I/Sx)	24	346.428	14.434	

P: pressure
Sp: speaker
Sx: sex of receiver (subject)
I/Sx: individual subjects within sex
4.760 needed for significance at the 0.05 level of confidence

<u>Phoneme /ɑ/</u>. At each of five experimental sessions each of four subjects was stimulated with the vibrotactile form of the phoneme /ɑ/ spoken by each of four different speakers. The experimental sessions differed only in terms of the amount of pressure presented to the subject's

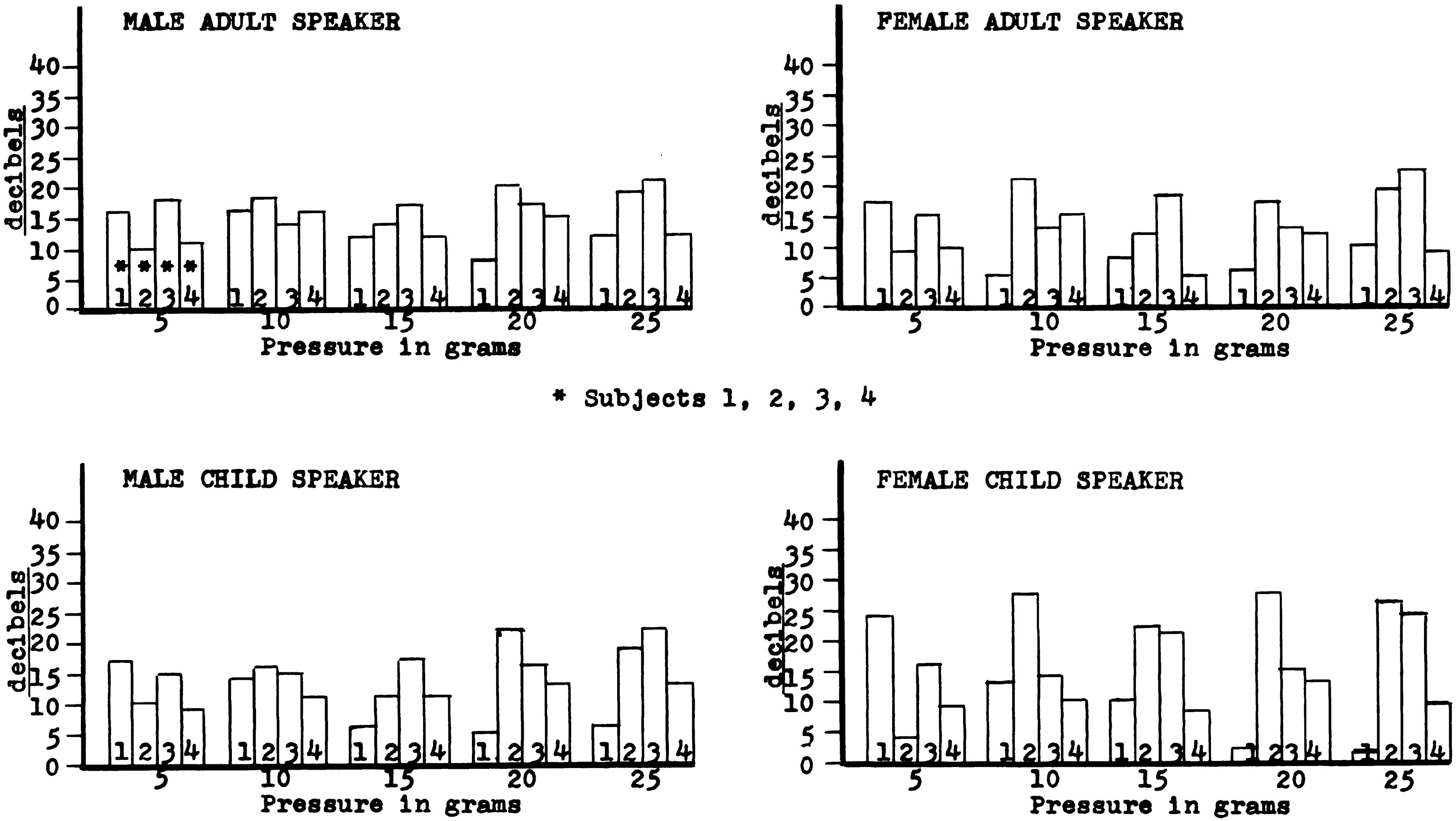


Figure 4. Phoneme /ʌ/. Each Speaker Versus All Subjects at All Pressures (0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

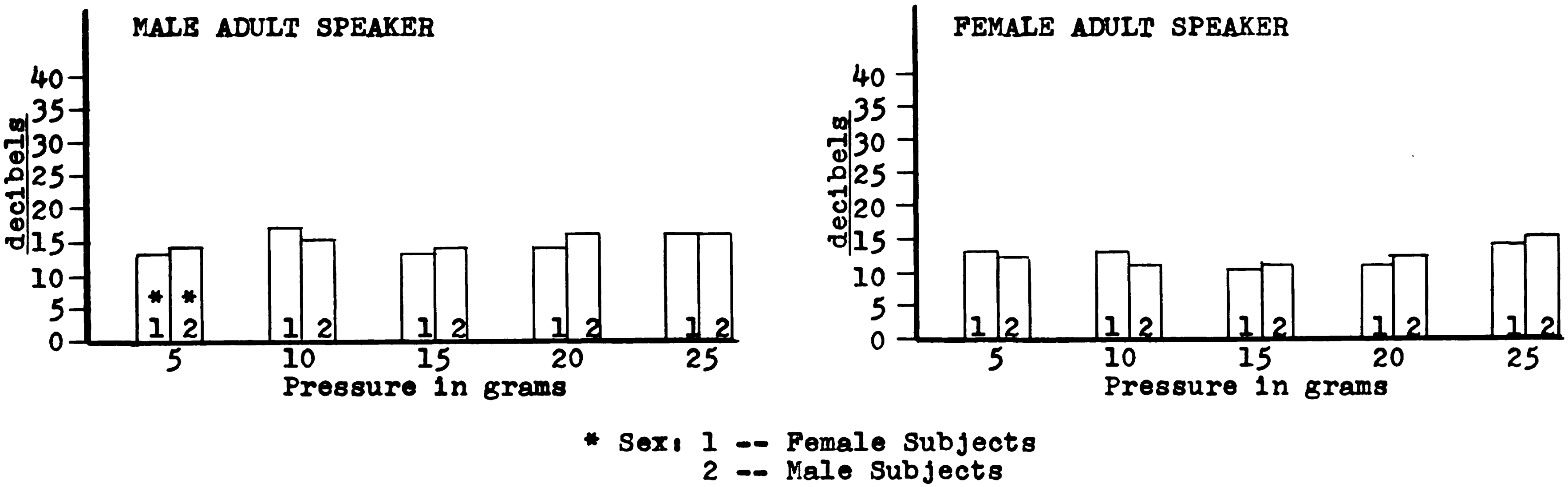


Figure 5. Phoneme /ʌ/. Each Speaker Versus Both Sexes at All Pressures
(0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

fingertip by the Bimorph's contactor rod. Two ascending and two descending threshold were established, the mean of the four comprising each subject's absolute threshold.

Figures 6 and 7 present the absolute threshold results in the form of histograms. Table 3 presents the statistical data obtained by analysis of variance. There were no significant effects attributable to any of the three variables or to interactions among them.

Table 3. Phoneme /ɑ/. Analysis of Variance: Threshold Data

Source	d/f	Sums of Squares	Mean Squares	F-Ratio
P	4	69.701	17.425	0.110
PSx	4	154.289	38.572	0.243
P(I/Sx)	8	1266.177	158.272	
Sp	3	295.712	98.570	4.451
SpSx	3	9.118	3.039	0.137
Sp(I/Sx)	6	132.858	22.143	
Sx	1	49.455	49.455	0.092
I/Sx	2	1065.386	532.693	
PSp	12	40.176	3.348	0.214
PSpSx	12	51.046	4.253	0.272
PSp(I/Sx)	24	375.062	15.627	

P: pressure
Sp: speaker
Sx: sex of receiver (subject)
I/Sx: individual subjects within sex
4.760 required for significance at the 0.05 level of confidence

<u>Phoneme /n/</u>. At each of five experimental sessions each of four subjects was stimulated with the vibrotactile form of the phoneme /n/ spoken by each of four different speakers. The experimental sessions differed only in terms

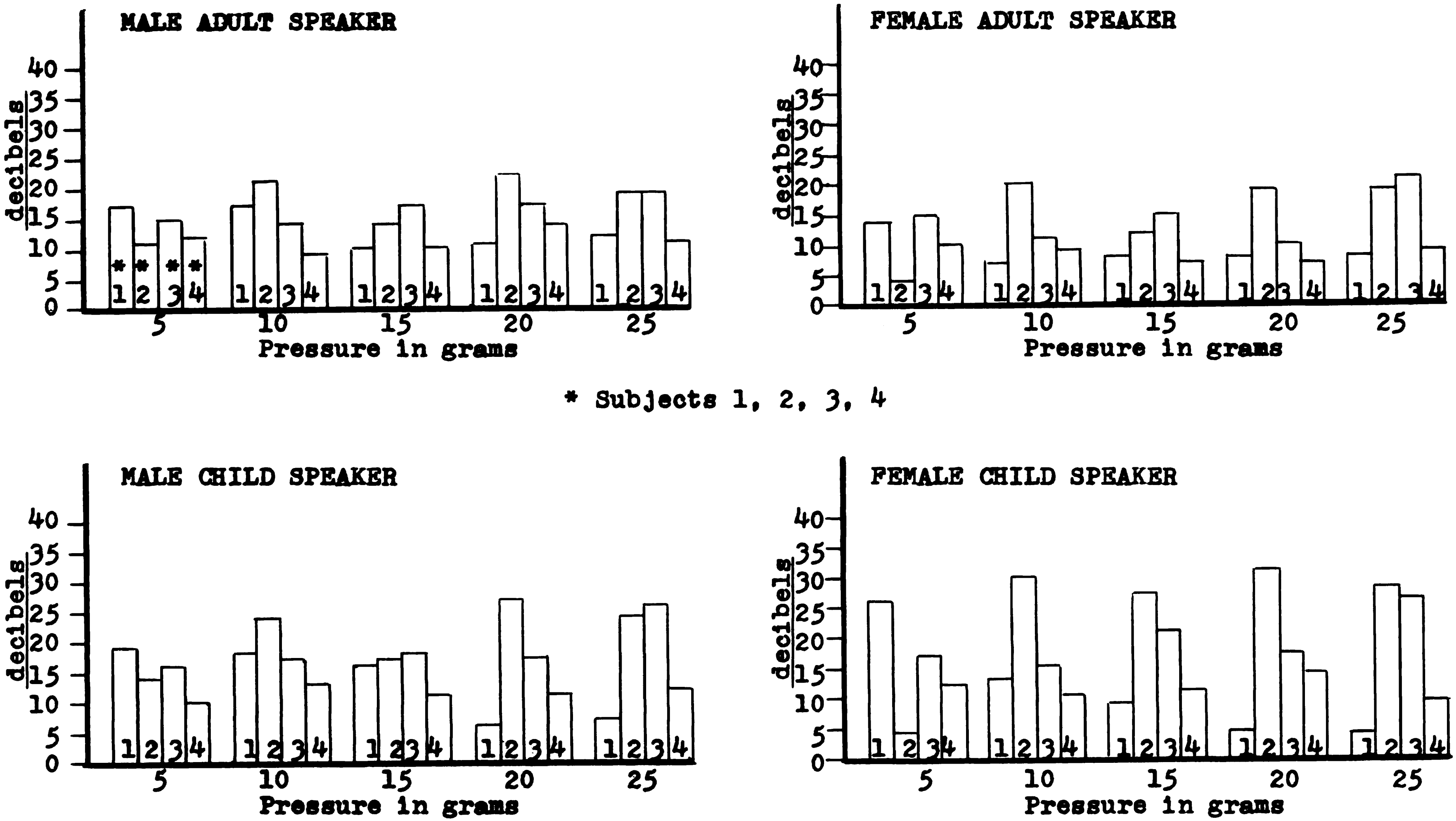


Figure 6. Phoneme /a/. Each Speaker Versus All Subjects at All Pressures (0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

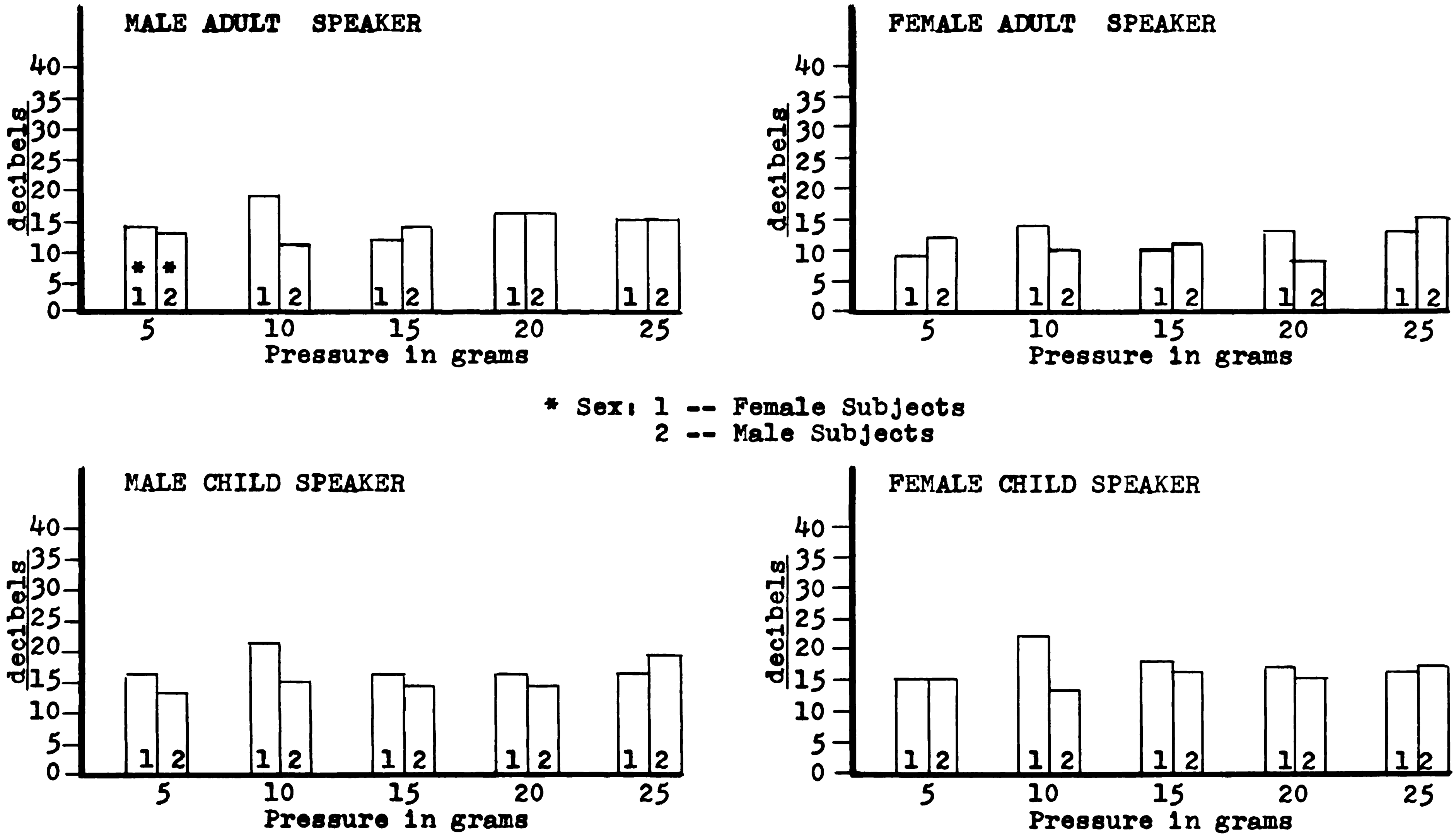


Figure 7. Phoneme /ɑ/. Each Speaker Versus Both Sexes at All Pressures (0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

of the amount of pressure presented to the subject's fingertip by the Bimorph's contactor rod. Two ascending and two descending thresholds were established, the mean of the four comprising each subject's absolute threshold.

Figures 8 and 9 present the absolute threshold results in the form of histograms. Table 4 presents the statistical data obtained by analysis of variance. There were no significant effects attributable to any of the three variables or to interactions among them.

Table 4. Phoneme /n/. Analysis of Variance: **Threshold Data**

Source	d/f	Sums of Squares	Mean Squares	F-Ratio
P	4	217.593	54.398	0.346
PSx	4	123.141	30.785	0.196
P(I/Sx)	8	1256.522	157.065	
Sp	3	118.415	39.471	1.087
SpSx	3	91.246	30.415	0.838
Sp(I/Sx)	6	217.726	36.287	
Sx	1	2.521	2.521	0.006
I/Sx	2	812.955	406.477	
PSp	12	31.952	2.662	0.169
PSpSx	12	47.712	3.976	0.252
PSp(I/Sx)	24	377.237	15.718	

P: pressure
Sp: speaker
Sx: sex of receiver (subject)
I/Sx: individual subjects within sex
4.760 required for significance at the 0.05 level of confidence

Phoneme /b/. At each of five experimental sessions each of four subjects was stimulated with the vibrotactile form of the phoneme /b/ spoken by each of four different

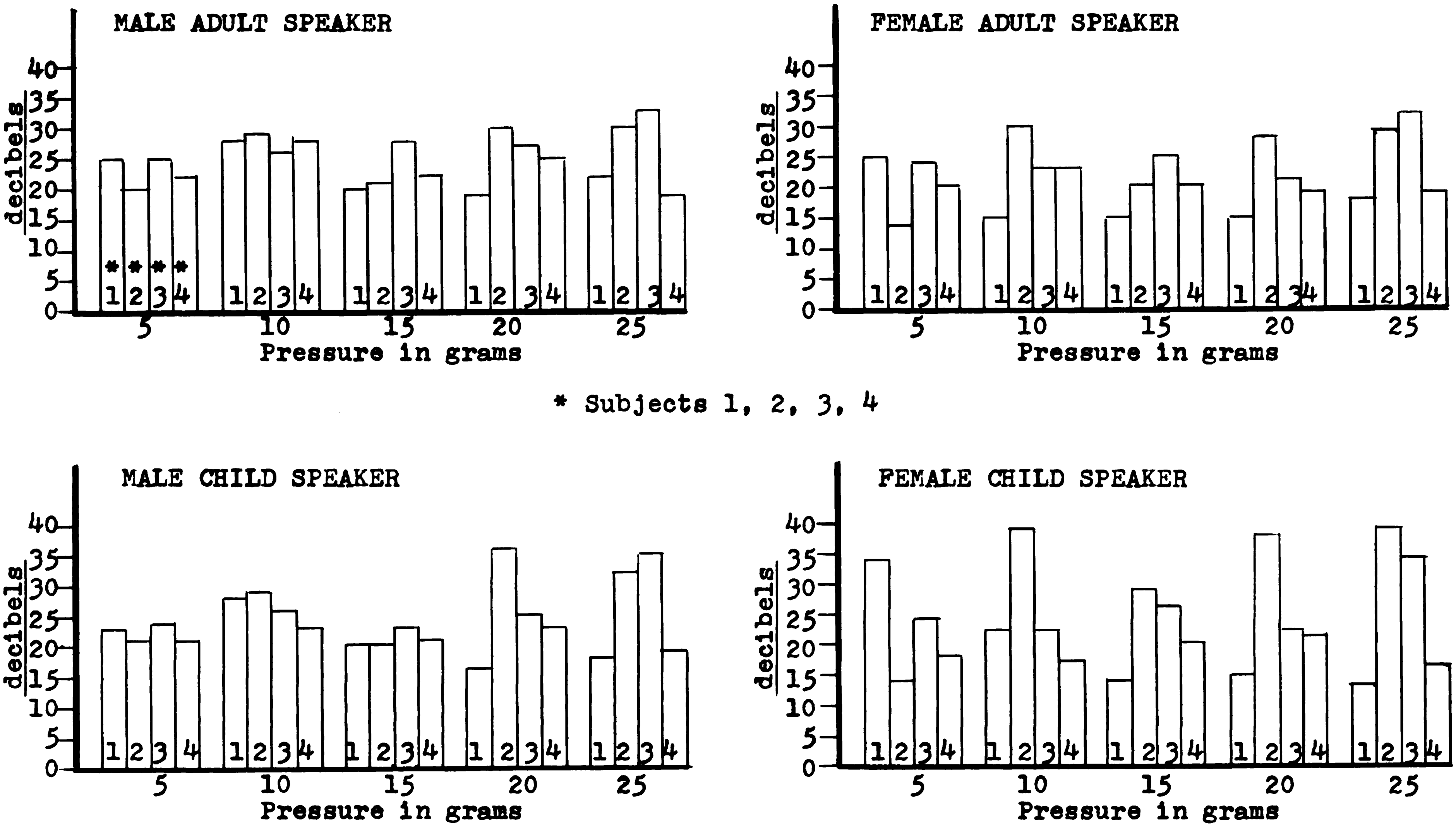


Figure 8. Phoneme /n/. Each Speaker Versus All Subjects at All Pressures (0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

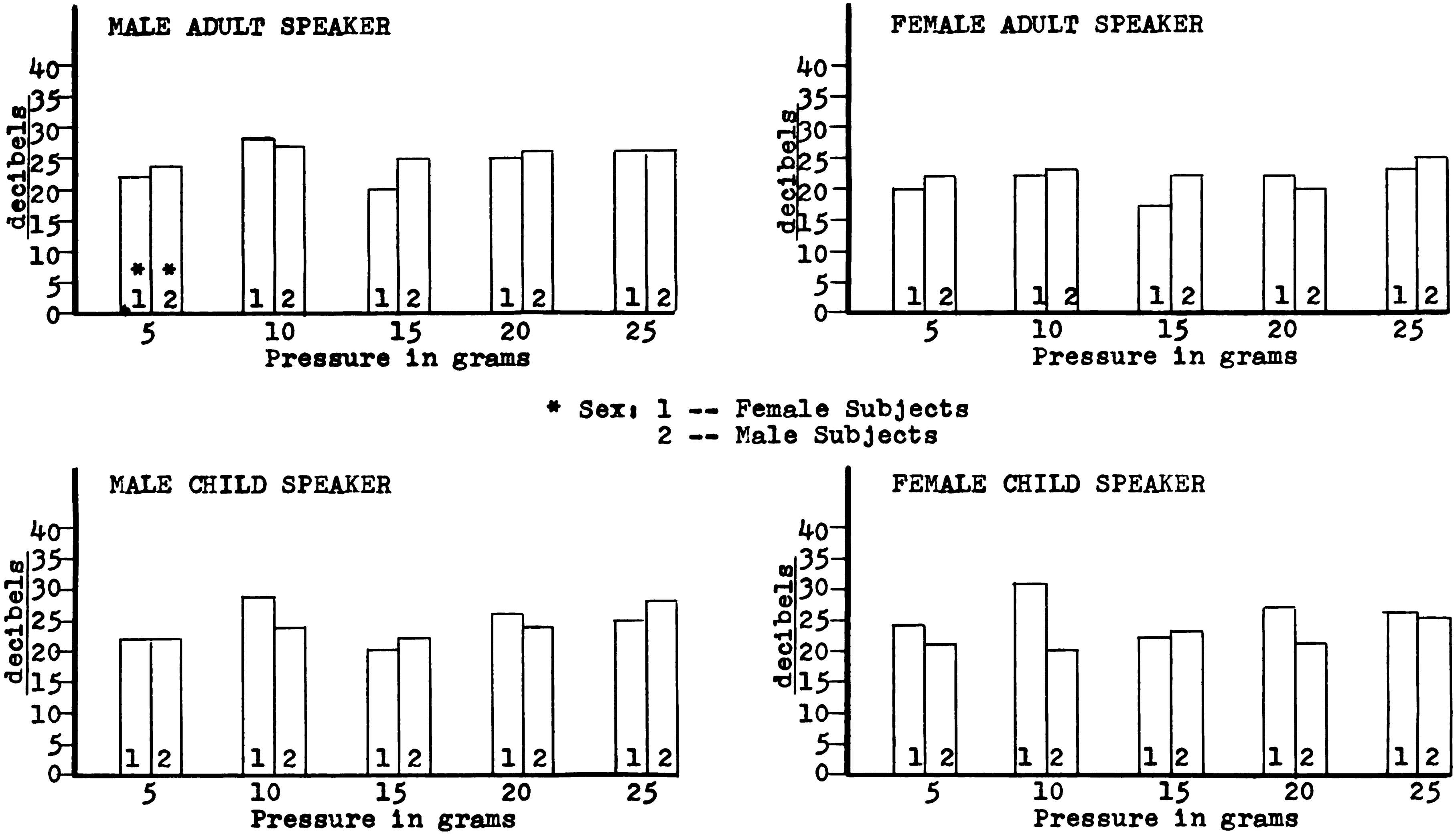


Figure 9. Phoneme /n/. Each Speaker Versus Both Sexes at All Pressures
(0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

speakers. The experimental sessions differed only in terms of the amount of pressure presented to the subject's fingertip by the Bimorph's contactor rod. Two ascending and two descending thresholds were established, the mean of the four comprising each subject's absolute threshold.

Figures 10 and 11 present the absolute threshold results in the form of histograms. Table 5 presents the statistical data obtained by analysis of variance. There were no significant effects attributable to the pressure or sex of receiver variables, nor were there any interaction effects among any of the variables. However, there was a speaker effect significant at the 0.05 level of confidence. This phenomenon will be discussed in the appropriate section of this chapter.

Table 5. Phoneme /b/. Analysis of Variance: Threshold Data

Source	d/f	Sums of Squares	Mean Squares	F-Ratio
P	4	168.998	42.249	0.320
PSx	4	182.669	45.667	0.346
P(I/Sx)	8	1053.921	131.740	
Sp	3	681.396	227.132	6.744*
SpSx	3	95.398	31.799	0.944
Sp(I/Sx)	6	202.051	33.675	
Sx	1	3.120	3.120	0.010
I/Sx	2	570.881	285.440	
PSp	12	73.796	6.149	0.410
PSpSx	12	41.163	3.430	0.228
PSp(I/Sx)	24	359.557	14.981	

P: pressure
Sp: speaker
Sx: sex of receiver (subject)
I/Sx: individual subjects within sex
*4.760 required for significance at the 0.05 level of confidence

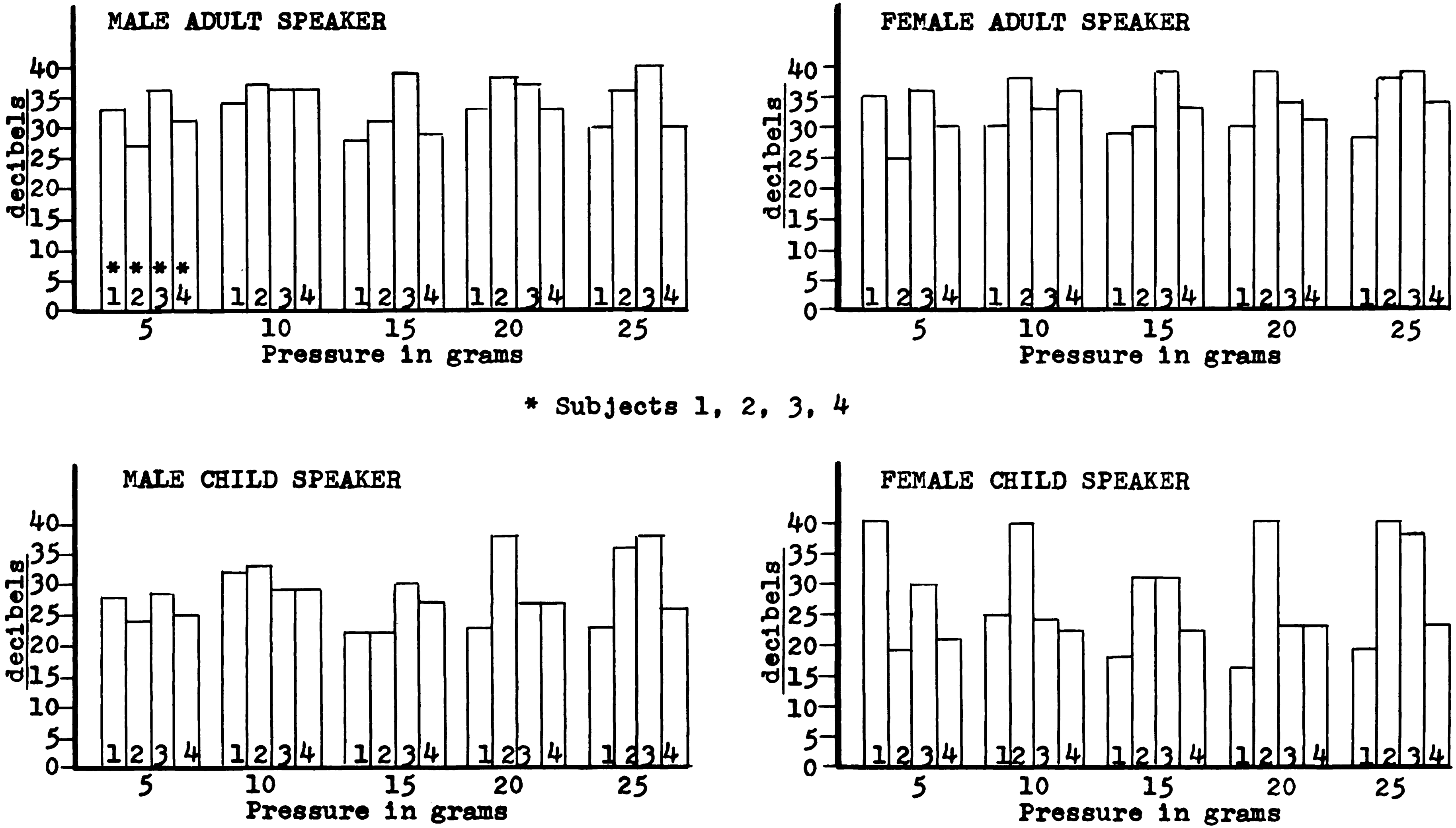


Figure 10. Phoneme /b/. Each Speaker Versus All Subjects at All Pressures (0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

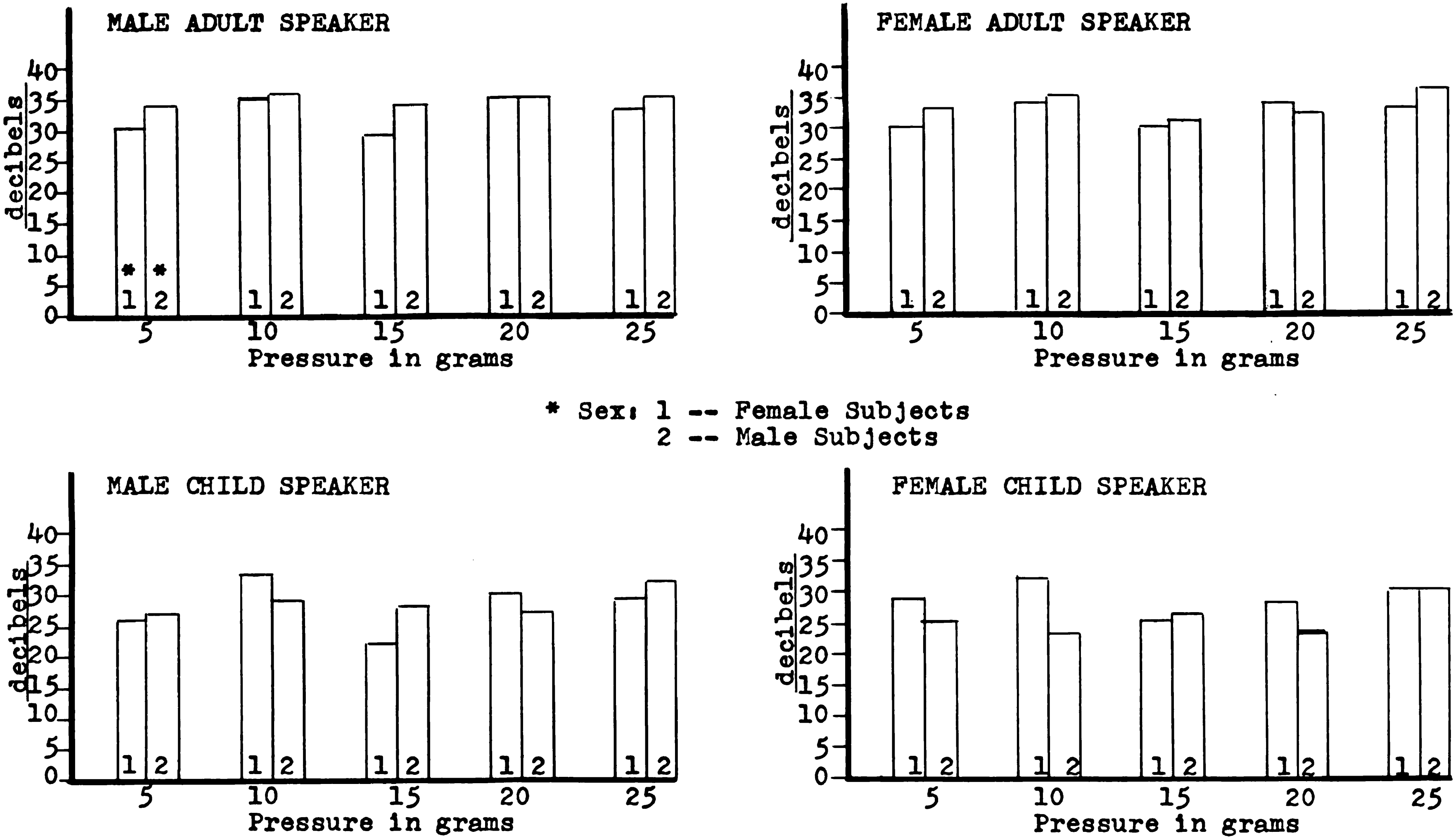


Figure 11. Phoneme /b/. Each Speaker Versus Both Sexes at All Pressures (0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone)

Agreement Among Subjects' Absolute Threshold Scores

The null hypothesis that there is no agreement among subjects for vibrotactile thresholds 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 ranks (Downie and Heath, 1965). The formula is:

$$W_c = \frac{\text{Sums of Squares Between Columns} - \frac{1}{m}}{\text{Total Sums of Squares} = \frac{2}{m}}$$

where m is equal to the number of subjects (judges).

For each of the experimental pressures used in this study, the responses of the four subjects to each of the four speakers were analyzed in turn. Tables 6-10 present the data and the W for each speaker under each pressure condition. Any result exceeding 0.669 indicated significant correlation of subject's rankings at the 0.01 level of confidence. Examination of the results will indicate that agreement among the subjects was significant at this level for each speaker at each experimental pressure level.

Further discussion of these data will be found in the appropriate section of this chapter.

Agreement Between Mean Thresholds: Haas and Present Study

Since the present study is a direct outgrowth of the investigation by Haas(1970), who established that thresholds for spoken English phonemes could be obtained by means of vibrotactile stimulation, a comparison of the mean threshdlds yielded by the two studies was deemed appropriate.

Table 6. Agreement Among Subjects' Absolute Thresholds: 5 Grams

Speaker	Receiver (Subject)	u	ʌ	ɑ	n	b	Kendall's W_c**
		Phoneme Rank*					
Male Adult	1	1	2	3	4	5	
	2	1	2	3	4	5	
	3	2	3	1	4	5	
	4	1	2	3	4	5	
							0.87
Female Adult	1	2	3	1	4	5	
	2	2	3	1	4	5	
	3	3	1.5	1.5	4	5	
	4	3	2	1	4	5	
							0.90
Male Child	1	1	2	3	4	5	
	2	2	1	3	4	5	
	3	3	1	2	4	5	
	4	3	1	2	4	5	
							0.87
Female Child	1	2	1	3	4	5	
	2	3	1.5	1.5	4	5	
	3	1	2	3	4	5	
	4	1	2	3	4	5	
							0.84

* Phonemes ranked from best (i.e., 1) to poorest (i.e., 5) thresholds for each subject

** 0.669 required for significance at the 0.01 level of confidence. All sets were significantly correlated at this level.

Table 7. Agreement Among Subjects' Absolute Thresholds: 10 Grams

Speaker	Receiver (Subject)	Phoneme Rank* u	ʌ	ɑ	n	b	Kendall's $\underline{W}_c$**
Male Adult	1	1	2	3	4	5	
	2	2	1	3	4	5	
	3	3	2	1	4	5	
	4	2	3	1	4	5	0.78
Female Adult	1	2	1	3	4	5	
	2	2	3	1	4	5	
	3	2	3	1	4	5	
	4	3	2	1	4	5	0.85
Male Child	1	1.5	1.5	3	4	5	
	2	2	1	3	4	5	
	3	2	1	3	4	5	
	4	2	1	3	4	5	0.96
Female Child	1	1	2.5	2.5	4	5	
	2	3	1	2	4	5	
	3	3	1	2	4	5	
	4	3	1	2	4	5	0.85

* Phonemes ranked from best (i.e., 1) to poorest (i.e., 5) thresholds for each subject

** 0.669 required for significance at the 0.01 level of confidence. All sets were significantly correlated at this level.

Table 8. Agreement Among Subjects' Absolute Thresholds: 15 Grams

Speaker	Receiver (Subject)	Phoneme Rank* u	ʌ	ɑ	n	b	Kendall's W_c**
Male Adult	1	1	3	2	4	5	
	2	3	1	2	4	5	
	3	1	2	3	4	5	
	4	3	2	1	4	5	0.78
Female Adult	1	3	1	2	4	5	
	2	3	1.5	1.5	4	5	
	3	1	3	2	4	5	
	4	3	1	2	4	5	0.80
Male Child	1	2	1	3	4	5	
	2	1	2	3	4	5	
	3	2	1	3	4	5	
	4	1	3	2	4	5	0.87
Female Child	1	1	3	2	4	5	
	2	2.5	1	2.5	4	5	
	3	1	2	3	4	5	
	4	2	1	3	4	5	0.84

* Phonemes ranked from best (i.e., 1) to poorest (i.e., 5) thresholds for each subject

** 0.669 required for significance at the 0.01 level of confidence. All sets were significantly correlated at this level.

Table 9. Agreement Among Subjects' Absolute Thresholds: 20 Grams

Speaker	Receiver (Subject)	Phoneme Rank* u	ʌ	ɑ	n	b	Kendall's $\underline{W}_c$**
Male Adult	1	2	1	3	4	5	
	2	1	2	3	4	5	
	3	1	2.5	2.5	4	5	
	4	2.5	2.5	1	4	5	
							0.81
Female Adult	1	1.5	1.5	3	4	5	
	2	2.5	1	2.5	4	5	
	3	2	3	1	4	5	
	4	3	2	1	4	5	
							0.79
Male Child	1	1	2	3	4	5	
	2	2	1	3	4	5	
	3	1	2	3	4	5	
	4	3	2	1	4	5	
							0.82
Female Child	1	2	1	3	4	5	
	2	3	1	2	4	5	
	3	1	2	3	4	5	
	4	1	2	3	4	5	
							0.87

* Phonemes ranked from best (i.e., 1) to poorest (i.e., 5) thresholds for each subject

** 0.669 required for significance at the 0.01 level of confidence. All sets were significantly correlated at this level.

Table 10. Agreement Among Subjects' Absolute Thresholds: 25 Grams

Speaker	Receiver (Subject)	Phoneme Rank* u	ʌ	ɑ	n	b	Kendall's $\underline{W}_c$**
Male Adult	1	1	3	2	4	5	
	2	1	3	2	4	5	
	3	3	2	1	4	5	
	4	1	3	2	4	5	
							0.87
Female Adult	1	2	3	1	4	5	
	2	3	1	2	4	5	
	3	1	3	2	4	5	
	4	3	1	2	4	5	
							0.80
Male Child	1	1	2	3	4	5	
	2	2	1	3	4	5	
	3	2	1	3	4	5	
	4	1.5	3	1.5	4	5	
							0.84
Female Child	1	1	2	3	4	5	
	2	3	1	2	4	5	
	3	3	1	2	4	5	
	4	3	1	2	4	5	
							0.87

* Phonemes ranked from best (i.e., 1) to poorest (i.e., 5) thresholds for each subject

** 0.669 required for significance at the 0.01 level of confidence. All sets were significantly correlated at this level.

Accordingly, the absolute thresholds recorded for all four subjects were combined and a mean threshold was obtained for each of the experimental phonemes. These mean thresholds were then ranked and compared with those recorded by Haas for the same phonemes. The statistical procedure used was the Spearman Rank Correlation for two sets of ranks (Hayes, 1963). The formula is:

$$r_s = 1 - \frac{6 \sum D^2}{n(n^2-1)}$$

where D^2 represents the square of the difference between any pair in the ranking and n represents the number of items ranked. The data are presented in Table 11. The correlation coefficient obtained in this instance was 0.90, which is significant for an n of five at the 0.05 level of confidence.

Table 11. Mean Threshold Agreement: Haas and Present Study

Phoneme	Haas' Ranking	Present Study Ranking
u	1	1
ʌ	2	3
ɑ	3	2
n	4	4
b	5	5

Discussion

Basic data relative to the effects of speaker, contactor pressure, and sex of the receiver on the thresholds for selected phonemes was provided by this study. The basis for undertaking the study was "an interest in vibrotactile information as a supplement to visual communication and to residual auditory function" (Haas, 1970). The hope is that the utilization of such data, together with that provided by additional studies into related areas of vibrotactile discrimination for speech stimuli, might ultimately lead to improved communication abilities for persons with significant hearing losses. The validity of this approach has been demonstrated by Haas' results. His investigation, however, provided information relative to only one speaker at one contactor pressure. Further, whereas Haas demonstrated a significant degree of agreement between his subjects, it did not indicate whether or not there were any response patterns which might correlate with sexual classification of the subjects.

Replicating Haas' study, except for the number of speakers and contactor pressures used, the present investigation was successful in evaluating the influence of speaker, contactor pressure, and sex variation on thresholds for selected spoken English phonemes.

Effects of Speaker, Contactor Pressure, and Sex of the Receiver. As was indicated earlier, there were no significant speaker, pressure, sex of the receiver, or interaction effects for any of the phonemes except /b/. In the latter instance, there was a speaker effect significant at the 0.05 level of confidence. A comparison of the overall

mean thresholds obtained for each of the four speakers for the phoneme /b/ indicated that there was an adult-child dichotomy; i.e., the thresholds obtained for the adult male and female speakers varied significantly from those obtained for the pre-adolescent male and female speakers. This may be observed in Figure 12, where the pattern displayed for the phoneme /b/ is seen to contrast with that displayed for the other phonemes.

The reason for this speaker effect occurring for the phoneme /b/ and not for the other phonemes is not apparent from the data yielded by this study, nor is it within the scope of this study to answer. However, it should be noted that this phoneme was the least stable of those included in the study. Absolute thresholds obtained by /b/, particularly from subjects two and three (a female and a male, respectively), often approached the limits of the equipment. This can be observed by reference to Figure 10. In the case of subject two, there were three instances where no absolute threshold for /b/ was ever established by the psychophysical method of limits, utilizing the four ascending and descending thresholds. Rather, responses were obtained only to the alerting signal given at the limits of the equipment (40 dB re tactile 0). In all such instances, the speaker was the female child. Specifically, this occurred at 10 grams, 20 grams, and 25 grams of contactor pressure. The same thing occurred once, again for the female child speaker, with subject one (a female) at 5 grams of contactor pressure

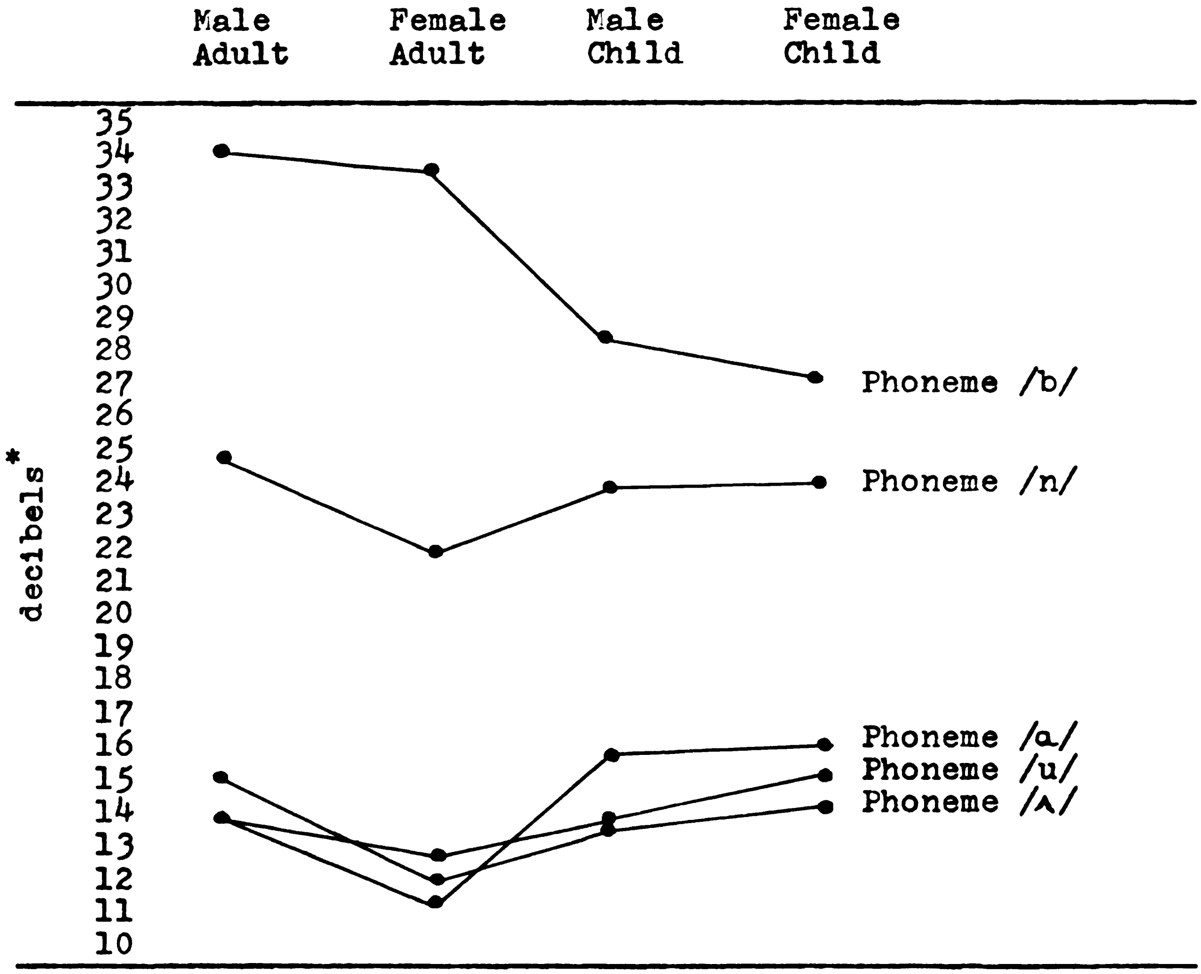


Figure 12. Overall $\bar{X}$: Speaker Versus Phoneme

* 0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone

As Haas pointed out, the phoneme /b/ is a relatively weak sound, both in terms of speech power and tactile rank. Fletcher (1953) listed it as the thirty-third phoneme out of thirty-six in terms of speech power, and Haas established it as being twenty-ninth out of thirty-six in terms of tactile threshold. Although it is not possible to generalize to the general population on the basis of the subjects used in this study, it is conceivable that the vibrotactile reception of /b/ uttered by pre-adolescent female speakers may not be particularly beneficial as a supplement to visual reception of /b/ if the pre-adolescent female speaker used in the present study is indeed representative of the general population of such speakers. Fortunately, /b/ is a highly visible phoneme; thus, the loss of supplementary vibrotactile information would not be particularly critical. On the other hand, the same pattern might be found to be true of other phonemes not tested in this study.

Agreement Among Subjects' Absolute Threshold Scores. It was initially intended to examine the agreement among subjects' absolute threshold scores only for that one specific pressure which proved to be optimum for all subjects. However, as stated earlier, there was no significant effect for any of the five experimental contactor pressures used in this investigation, insofar as the analysis of variance was concerned. As a result, agreement among subjects' absolute threshold scores was examined for all five pressures. All pressures resulted in good agreement among the subjects for all four speakers. This is an expanded confirmation of the significant agreement Haas found for one speaker at one pressure.

It was hoped, for the benefit of those who will investigate other parameters of vibrotactile reception of spoken English phonemes in the future, that the optimum contactor pressure might be determined. As pointed out, no objective data tend to recommend one pressure over another. However, subjective comments by two of the subjects indicate that Geldard's (Haas, 1970) recommended pressure of 15 grams (± 5 grams) is indeed best. One male subject (subject four) indicated that he found the contactor pressure of 25 grams exhausting. On the other hand, a female subject (subject one) said that she found the contactor pressure of 5 grams difficult. A visual examination of subject performances at the various pressures, as seen in Figures 2, 4, 6, 8, and 10, will show that subject four's responses at 25 grams of pressure were essentially the same as for the other pressures, in spite of the fact that he found it more difficult. On the other hand, subject one's responses at the other pressures were better, though not significantly so, than at 5 grams.

The other two subjects indicated that they did not find one pressure preferable to another.

Agreement Between Mean Thresholds: Haas and Present Study. As pointed out earlier in this chapter, and as can be observed in Table 11, the subjects in both Haas' investigation and the present study were in significant agreement with regard to their ranking of the phonemes selected for examination in this study. It will be noted that the rankings for the phonemes /ʌ/ and /ɑ/, which Haas' subjects placed in the second and third positions respectively, were inverted by subjects in the present study. However, this inversion was not enough to destroy the significance of agreement.

An examination of Figure 13 and Table 12 will

disclose a curious phenomenon, however. The tactile thresholds yielded by Haas' subjects for the phonemes under investigation in the present study were spread out, each adjacent phoneme separated by a minimum of 3 dB. Indeed, this was one of the criteria used in selection of the phonemes to be used in the present study. On the other hand, whereas the consonant thresholds obtained in the present study follow the same general slope as those obtained by Haas, vowels in the present study are all clustered at approximately the same dB level. This pattern held true, in general, for all subjects in the present study, at all pressures, for all speakers. Whereas Haas noted a significant correlation between the relative speech power and the tactile rank of the phonemes, this correlation appears to be even stronger for the present study. An actual computation of the correlation for the present study would be meaningless, however, since the relative speech powers specified by Fletcher (1953) for the three vowels under consideration are contained within an overall 3 dB range, and the criteria for this study dictated that the experimental phonemes be adjusted to meet Fletcher's criteria, plus or minus 2 dB.

It should also be noted that the thresholds obtained by the present study are, in general, poorer than those obtained by Haas, approaching each other for the phoneme /ɑ/, only. This pattern also holds true, in general, throughout the present study. It was apparently for this reason that no threshold could be established for the phoneme /h/,

Table 12. Absolute Thresholds for Experimental Phonemes*: Haas and Present Study

Phonemes	dB** Haas	dB** Present Study
u	3.7	12.7
ʌ	7.0	13.3
ɑ	11.8	12.8
n	17.3	22.8
b	22.4	31.7

* Using adult male General American speakers at 15 grams contactor pressure

** 0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone

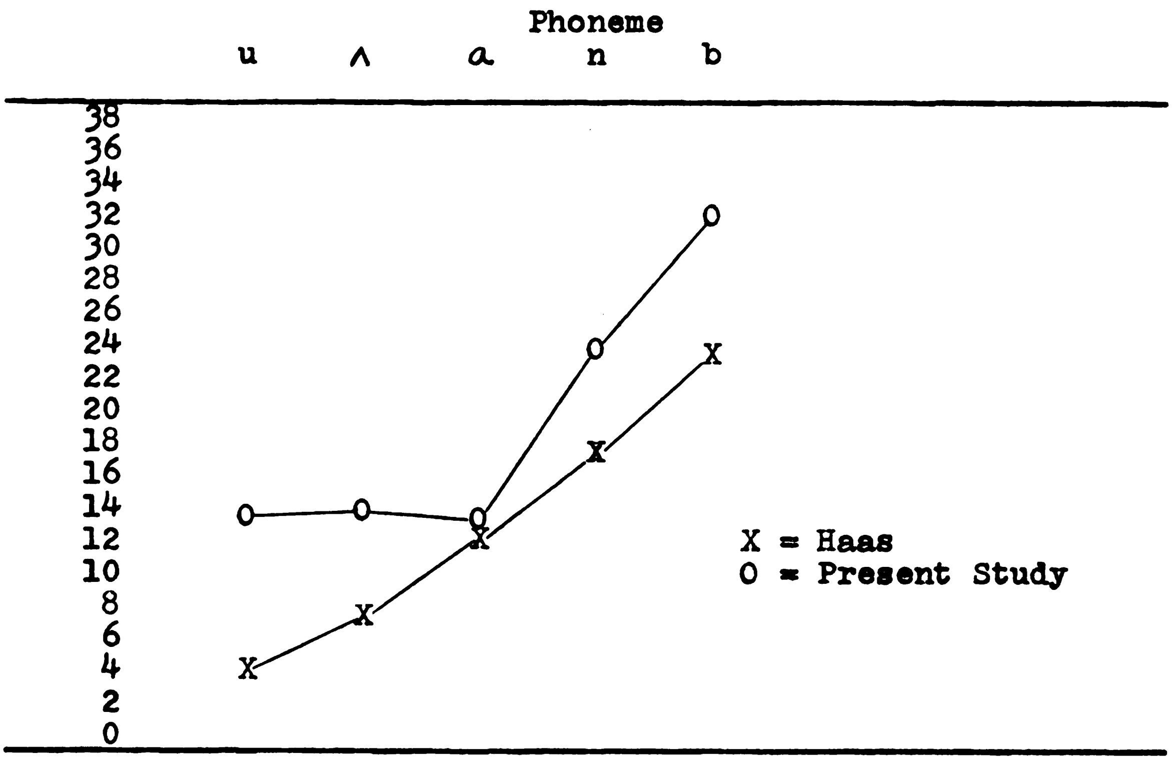


Figure 13. Absolute Thresholds for Experimental Phonemes*: Haas and Present Study

* 0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone

** Using adult male General American speakers at 15 grams contactor pressure originally chosen to be one of the experimental phonemes in this study. Haas obtained a mean threshold for this phoneme at 30.1 dB (re tactile 0). The present study obtained no responses to the phoneme, which Haas described as having a high frequency composition together with low speech power. Of thirty-six phonemes he investigated, /h/ ranked thirty-sixth with regard to speech power and thirty-fourth in tactile threshold placement.

Although any explanation of these discrepancies is purely a matter of conjecture, possible explanations which have been considered are speaker differences, subject differences, differences in the preparation and/or administration of the materials, and equipment differences.

Whereas it is true that all speakers used in the present study were different from the one used by Haas, it is also true that all four speakers used in the present study yielded essentially the same pattern with regard to the clustering of the vowel phonemes, and poorer thresholds as compared with the Haas study. Analysis of variance between speakers indicated that the speakers in the present study came from the same population, i.e., differences were not significant. Therefore, unless Haas' speaker came from a different population, the answer to the discrepancies must be sought elsewhere.

With regard to differences in the preparation and/or administration of the materials, consultation with various personnel who were actively involved in the preparation and administration of the Haas materials, as well as a telephone conversation with Haas himself, suggests that it is not in this area where the answer to the discrepancy may be found.

The equipment utilized was either the same as that used by Haas or met the same specifications. The one exception was the Bimorph itself. Although the apparatus housing the Bimorph was the same as that used by Haas, the actual Bimorph used in the transmission system was different. The one used in the Haas study had been damaged and was replaced. As this study was undertaken, calibration was checked with regard to the voltage across the Bimorph terminals at various readings on the audiometer dial. The results were identical to those recorded by Haas. Quality control by the Clevite Corporation is claimed to be such that each Bimorph of the same type will conform to the same response characteristics. This may very well be. Further, there is nothing but circumstantial evidence to suggest that the differences noted are attributable to the Bimorph. However, it does seem apparent that if further threshold investigation involving the Bimorph is contemplated, a comparison of such equipment should be made and some norms be established with regard to vibrotactile thresholds for the various phonemes.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Four subjects responded to tape recordings of English phonemes spoken by four General American speakers, i.e., an adult male, an adult female, a pre-adolescent male, and a pre-adolescent female. The experimental phonemes were selected from those used in a 1970 study by Haas. Each subject responded to each speaker under five conditions consisting of different levels of contactor pressure on the fingertip.

Analysis of variance was employed to determine whether or not there was any significant effect on the threshold level of phonemes attributable to speaker variation, contactor pressure variation, sex of the receiver (subject), or interactions between any of the preceding factors. The results indicate that for four of the experimental phonemes, i.e., /u/, /ʌ/, /ɑ/, and /n/, there were no significant effects due to any of the aforementioned factors or interactions. For the fifth phoneme, /b/, although no significant effects were found for pressure or sex variations or any interactions, a speaker effect was noted at the 0.05 level of significance. Further examination indicated that this speaker effect was due to a threshold dichotomy between adults and children. The reason for this dichotomy was not apparent from the data available for analysis, but it was noted that the phoneme /b/ was less stable than the others, particularly for the pre-adolescent female speaker. Further, it was noted that the phoneme /b/ was shown by Haas to be a relatively weak sound, both in terms of speech power and tactile rank. It was hypothesized that, if the pre-adolescent female speaker should prove to be representative of the population of pre-adolescent female speakers, vibrotactile reception of the phoneme /b/ may not be of significant benefit as a supplement to visual reception of that phoneme. Although this would not be of critical importance for the highly visible phoneme /b/, it was suggested that the same pattern might be true of other phonemes not tested in this study.

Haas demonstrated that there was excellent agreement among subjects' absolute threshold scores, using one speaker and one pressure. The same was found to be true in the present study for all speakers at all pressure levels. Although no one pressure or pressure range stood out from the others as being preferable insofar as objective analysis was concerned, subjective evaluations by the subjects indicated that 15 grams of contactor pressure on the fingertip, plus or minus 5 grams, was to be preferred.

Comparison of mean thresholds obtained by Haas and the present study showed a significantly high correlation. However, it was pointed out that whereas Haas obtained a consistent slope in the thresholds recorded for the experimental phonemes, results of the present study had the three experimental vowels clustered together near the same threshold, with the consonants following a slope similar to that yielded by Haas' subjects. It was noted that means in the present study correlated even more highly with the relative speech power levels of the phonemes than did Haas', although Haas found this correlation to be significant.

Further, it was noted that thresholds for the phonemes were generally poorer in the present study than those obtained by Haas, with the exception of the threshold for /ɑ/.

Various possible explanations for the differences in slope and threshold shown by the two studies were briefly discussed. Although it was not possible to specifically state the reason for the discrepancies, the most obvious potential cause to be investigated seemed to be possible differences in Bimorph responses to speech signals. It was pointed out that the Bimorph used by Haas was damaged and a different Bimorph of the same type was utilized in the present study.

Conclusions

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

1. Different speakers do not differentially affect the tactile perception of the phonemes /u/, /ʌ/, /ɑ/, /n/,

whereas a speaker effect, significant at the 0.05 level of confidence, was obtained for the phoneme /b/. The foregoing statement applies to both adult and pre-adolescent speakers, as well as male and female speakers.

2. Varying the contactor pressure of the Bimorph on the subject's fingertip does not affect the threshold level of the phonemes /u/, /ʌ/, /ɑ/, /n/, and /b/. The pressures used were 5, 10, 15, 20, and 25 grams beyond the point where the subject just began to detect contact.

3. Irrespective of the sex of the receiver (subject), the threshold level of the phonemes /u/, /ʌ/, /ɑ/, /n/, and /b/ was not differentially affected.

4. There are no interactions attributable to manipulation of the speaker-pressure, speaker-sex of subject, or pressure-sex of subject variables which are apparent for the phonemes /u/, /ʌ/, /ɑ/, /n/, and /b/.

5. The tactile detection threshold responses among subjects show excellent agreement for the phonemes /u/, /ʌ/, /ɑ/, /n/, and /b/.

6. The mean tactile detection thresholds obtained by Haas, using a single adult male speaker at 15 grams of contactor pressure on the fingertip, correlate significantly with those obtained in the present study.

Recommendations for Further Research

In view of the findings of the present investigation, the following recommendations for additional research are made:

1. It is suggested that a comparison of PZT-5B Bimorph threshold responses for spoken English phonemes be made, utilizing the same stimulus materials but a selection of Bimorphs of the same type, and that criteria be established as to what should constitute normal thresholds for the various phonemes. This would permit an objective evaluation of a Bimorph's sensitivity prior to using it in research projects.

2. A study designed to measure the effects of a larger sample of pre-adolescent female speakers on subjects' responses to the phoneme /b/ is an obvious priority. This would serve to indicate whether or not the difficulty experienced by some subjects with the pre-adolescent female speaker in the present study was attributable to chance or is characteristic of that population as a whole.

3. A study designed to measure the effects of a larger sample of all four types of speakers employed in the present study on subjects' responses to the phoneme /b/ is needed. This would serve to indicate whether or not the adult-child dichotomy found in the present study was attributable to chance or is a characteristic of the phoneme.

4. It would seem appropriate to compare the thresholds yielded by phonemes adjusted to the relative intensity

criteria specified by Fletcher to the same phonemes spoken by the same speaker but not adjusted for relative intensity.

5. Studies designed to compare the effect, on subjects' threshold responses, of speakers judged to be normal with speakers judged to have voice quality defects would be of interest. Likewise, a comparison of the responses to General American speakers as opposed to speakers with regional dialects could be conducted.

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APPENDICES

APPENDIX 1

HAAS' MEAN VIBROTACTILE THRESHOLDS FOR SPOKEN ENGLISH PHONEMES

APPENDIX 1

HAAS' MEAN VIBROTACTILE THRESHOLDS FOR SPOKEN ENGLISH PHONEMES

Table 13. Haas' Thresholds for English Phonemes (Haas, 1970).

Phoneme	Detection Threshold
u	3.7 dB*
o	5.1
ɪ	5.3
ɛ	5.7
ŋ	5.7
ʊ	6.4
ʌ	7.0
e	7.2
i	7.3
l	9.1
w	9.5
aʊ	9.6
ɔ	9.6
ɝ	10.1
aɪ	10.3
ɔɪ	10.4
ɑ	11.8
j	12.2
æ	12.2
v	12.9
p	13.2
m	17.1
n	17.3
k	19.0
g	19.1
tʃ	19.8
dʒ	19.8
d	20.0
b	22.4
t	22.6
ð	22.7
z	23.2
ʒ	25.1
h	30.1
ʃ	43.3
f	44.3

* 0 dB re 1.6 volts across Bimorph for 1,000 Hz calibration tone

APPENDIX 2

CHARACTERISTICS OF THE BIMORPH

APPENDIX 2

CHARACTERISTICS OF THE BIMORPH

The material comprising this appendix, including the three Figures, is taken directly from Haas (1970), pages 65-71, and 135.

> 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 [14] illustrates this arrangement.
>
> The framework for housing the Bimorph involved a cantilever mounting, also illustrated in Figure [14].
>
> 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 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.
>
> The skin-contactor coupler was a Lucite rod, 1/8 inch in diameter. The contactor was secured to the outermost 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 [15] illustrates this arrangement. The construction provided an 1/8 inch extension

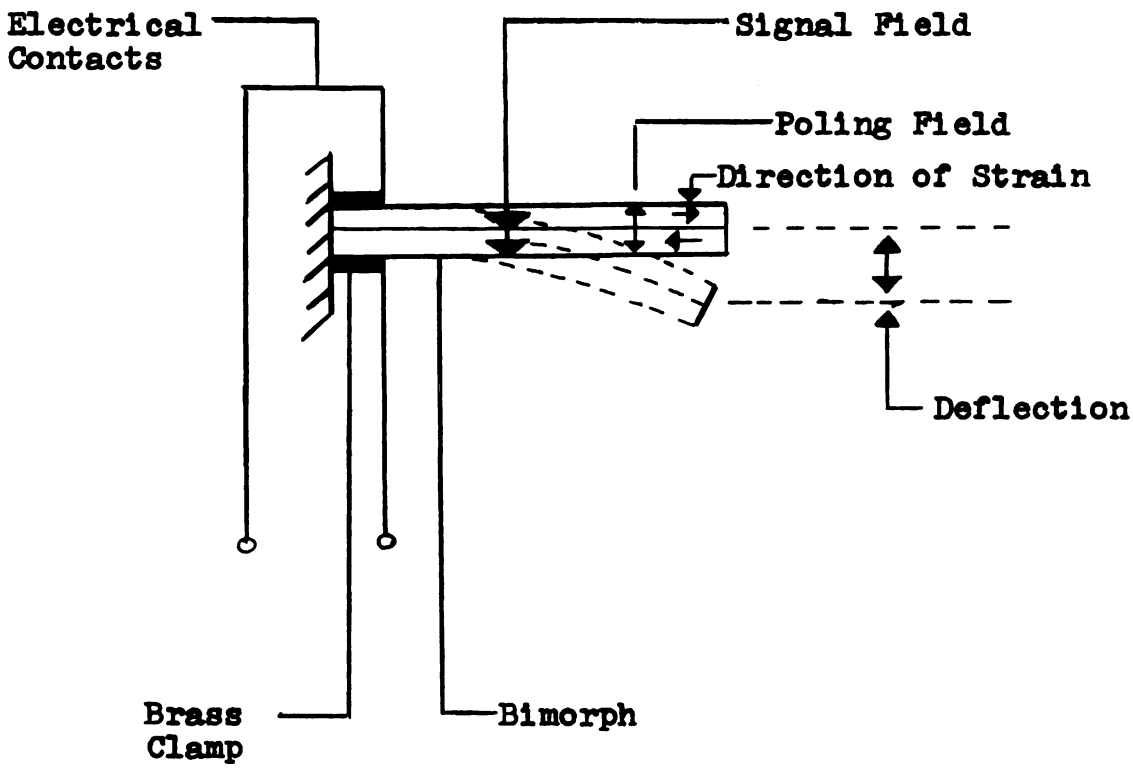

Figure 14. Cantilever Mounted Bimorph

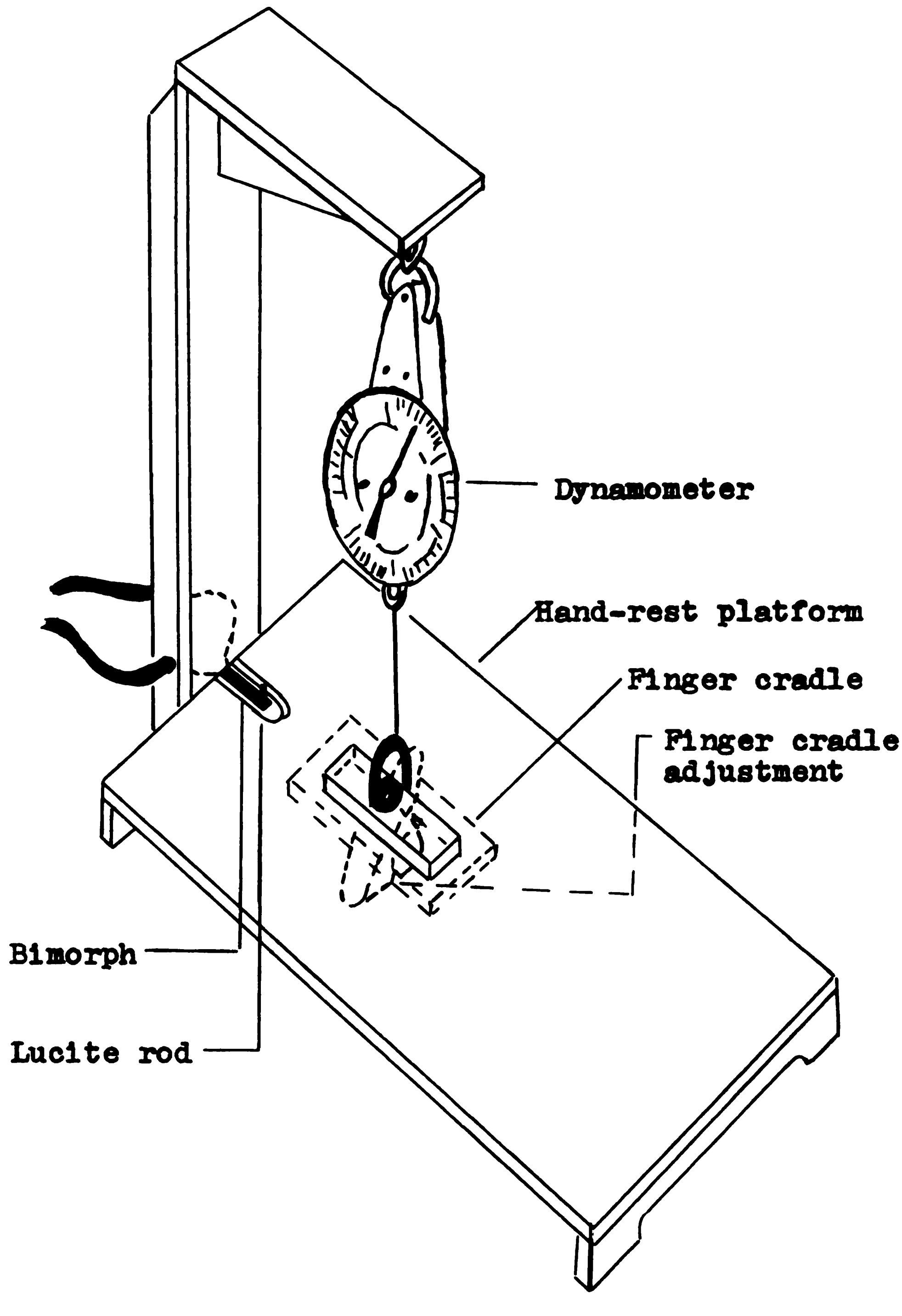

Figure 15. Apparatus for Housing Bimorph (PZT-5B)

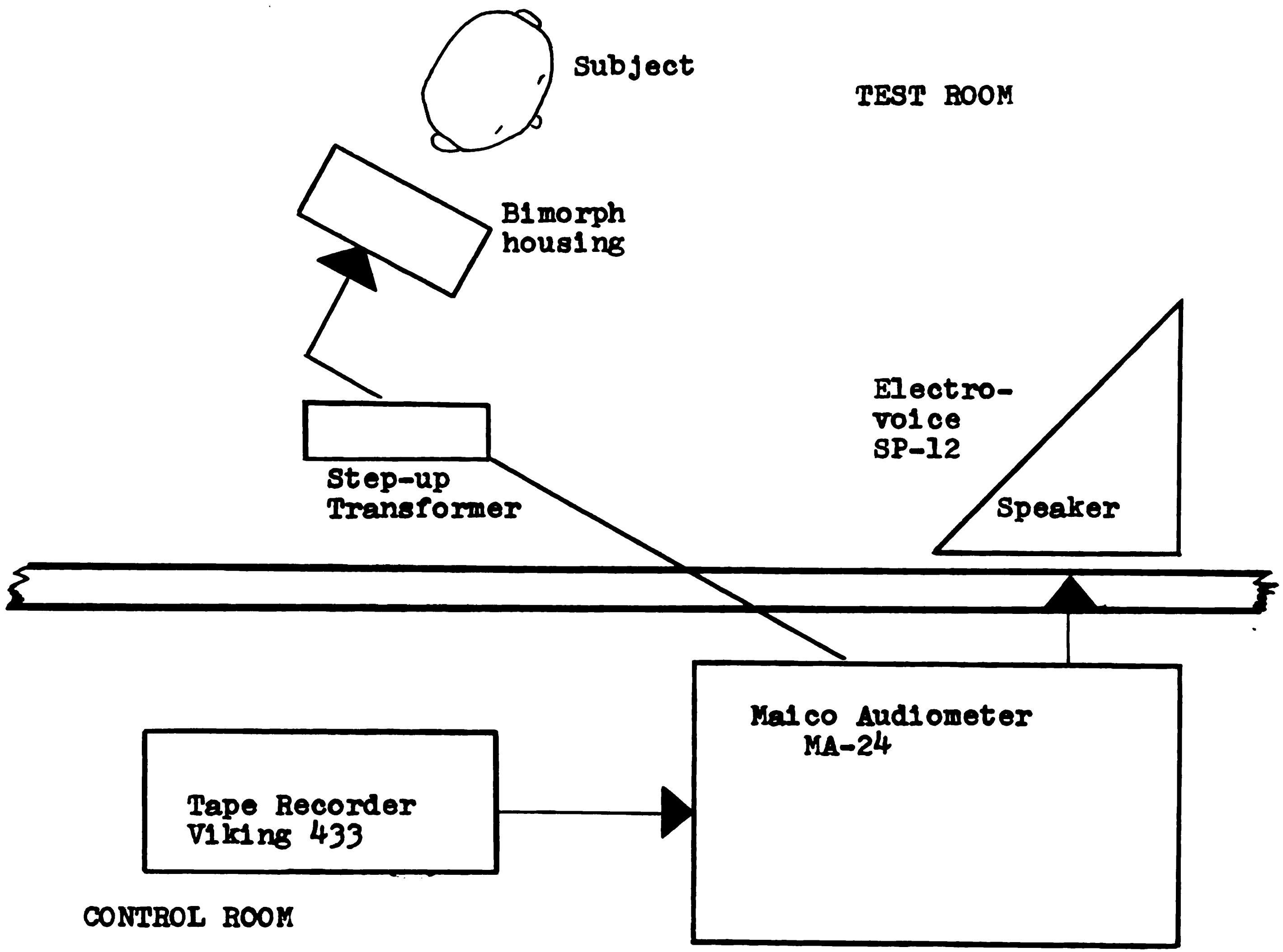

Figure 16. Schematic Diagram of Stimulus Transmission System, Test Room, and Adjoining Control Room.

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 handrest 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. . . . 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 . . . .

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 15 depicts this construction.

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 <u>Technical Publication</u> 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 3

A COMPARISON OF METHODS FOR DETERMINING ABSOLUTE VIBROTACTILE THRESHOLDS

APPENDIX 3

A COMPARISON OF METHODS FOR DETERMINING ABSOLUTE VIBROTACTILE THRESHOLDS

In his investigation, Haas (1970) used the psychophysical method of limits to determine absolute vibrotactile thresholds. Specifically, he used eight threshold measures, four ascending and four descending, and took their mean as the absolute threshold. In order to conserve time in what was expected to be a fatiguing series of experimental conditions in the present study, the feasibility of using only four threshold measures, i.e., two ascending and two descending, was investigated.

Looking at the six experimental phonemes to be used in the present study, and utilizing Haas' raw data, a comparison was made between the absolute thresholds Haas would have obtained using only his first four thresholds to compute the mean and those he actually obtained with the series of eight thresholds. Table 14 contains the results for all six of Haas' subjects, each presented separately.

It will be noted that differences obtained were insignificant, without exception. Further, all subjects ranked the six experimental phonemes identically under both conditions. This held constant within and between subjects.

On the basis of these results, it was decided that it would be acceptable to use only four threshold series.

Table 14. A Comparison of Means for Four Versus Eight Thresholds.

Subject	Phoneme	4 Threshold $\bar{X}$	8 Threshold $\bar{X}$	Δ
1	u	3.3	3.5	0.2
	ʌ	8.0	7.8	0.2
	ɑ	11.5	11.4	0.1
	n	16.0	15.6	0.4
	b	24.3	24.0	0.3
	h	30.3	30.2	0.1
2	u	4.5	4.8	0.3
	ʌ	6.3	5.6	0.7
	ɑ	12.8	12.5	0.3
	n	20.8	20.9	0.1
	b	24.8	24.5	0.3
	h	29.0	29.2	0.2
3	u	6.0	5.6	0.4
	ʌ	10.3	10.0	0.3
	ɑ	13.7	13.7	0.0
	n	18.8	19.6	0.8
	b	22.3	22.1	0.2
	h	28.5	28.2	0.3
4	u	0.8	0.5	0.3
	ʌ	6.0	5.6	0.4
	ɑ	10.3	9.5	0.8
	n	18.5	17.8	0.7
	b	20.0	19.9	0.1
	h	31.0	31.1	0.1
5	u	2.0	2.0	0.0
	ʌ	5.5	4.9	0.6
	ɑ	12.0	11.7	0.3
	n	14.3	13.7	0.6
	b	20.8	21.2	0.4
	h	30.3	29.9	0.4
6	u	6.5	6.9	0.4
	ʌ	8.5	8.4	0.1
	ɑ	11.8	11.8	0.0
	n	16.8	16.3	0.5
	b	23.5	23.0	0.5
	h	31.5	31.6	0.1

APPENDIX 4

RELATIVE INTENSITIES (SPEECH POWERS) OF PHONEMES

APPENDIX 4

RELATIVE INTENSITIES (SPEECH POWERS) OF PHONEMES

Table 15. Relative Intensities (Speech Powers) of Phonemes

Phoneme	Relative Intensity (Speech Power)					
	Fletcher* (1953)	Haas** (1970)	Present Study**			
			Male Adult	Female Adult	Male Child	Female Child
ɔ	28.0	28.0	28.0	28.0	28.0	28.0
u	25.0	24.9	25.5	27.0	26.0	25.5
ʌ	27.0	27.0	27.5	27.0	27.0	27.5
ɑ	28.0	27.7	28.5	28.5	27.5	27.5
n	16.0	15.5	18.0	17.0	16.5	16.5
b	9.0	8.4	11.0	10.0	11.0	11.0
h	4.0	4.0	5.5	6.0	3.0	3.0

* Fletcher's criteria were used as the standard to be met by Haas and the present study

** For Haas' investigation and the present study, the original speech power of the phonemes, as spoken by the respective speakers, were adjusted to meet Fletcher's criteria plus or minus 2 dB.

APPENDIX 5

RESPONSE CHARACTERISTICS OF RECORDING EQUIPMENT

APPENDIX 5

RESPONSE CHARACTERISTICS OF RECORDING EQUIPMENT

Electrovoice 635-A Recording Microphone. The Electrovoice 635-A recording microphone was placed in the Hearing Aid Test Box (Type 4212), symmetrically opposite to the regulating microphone. The output from the microphone being tested was fed into the Microphone Amplifier (Bruel & Kjaer Type 2604). A 60 dB signal generated from a Beat Frequency Oscillator (Bruel & Kjaer Type 1022) into the Hearing Aid Test Box sound field was used together with the amplifier section of an Audio Frequency Spectrometer (Bruel & Kjaer Type 2112) and a Graphic Level Recorder (Bruel & Kjaer Type 2305) to record the frequency response curve by the graphic level recorder. The results indicated that the Electrovoice 635-A recording microphone conformed to the manufacturer's standards (i.e., ± 2 dB from 100 to 15,000 Hertz, and - 5 dB from 60 to 100 Hertz).

Ampex AG-440B-4 Tape Recorder. The frequency response characteristics of this tape recorder were evaluated with an Ampex (7 1/2 ips) Precision Alignment Tape (NAB). The frequency response of the recorder was found to meet the manufacturer's specifications (i.e., ± 2 dB from 50 to 15,000 Hertz).

Ampex AG-600 Tape Recorder. The frequency response characteristics of this tape recorder were also evaluated with an Ampex (7 1/2 ips) Precision Alignment Tape (NAB).

The frequency response of this recorder was found to meet the manufacturer's specifications (i.e., $\pm$ 2 dB from 50 to 12,000 Hertz).

APPENDIX 6

FREQUENCY RESPONSE CHARACTERISTICS OF THE TACTILE STIMULUS TRANSMISSION SYSTEM

APPENDIX 6

FREQUENCY RESPONSE CHARACTERISTICS OF THE TACTILE STIMULUS TRANSMISSION SYSTEM

Viking 433 Tape Recorder. The frequency response characteristics of the Viking 433 Tape Recorder were evaluated by using an Ampex (7 1/2 ips) Precision Alignment Tape (NAB). The frequency response values 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, and 0 dB at 50 Hz.

Electrovoice SP-12 Loudspeaker. Utilizing a signal of broad band white noise, the response characteristics of the Electrovoice SP-12 loudspeaker were evaluated. With the audiometer dial of channel two of the Maico MA-24 audiometer set at 80 dB, the broad band white noise was fed into the loudspeaker. Measurements were made with the experimenter in the sound field at the position of the center of a subject's head. The Sound Level Meter (Bruel & Kjaer Type 2203) was used, together with its associated octave band filter network (Bruel & Kjaer Type 1613). The overall level on the C scale was not significantly different from 80 dB SPL.

Bimorph. The Pulse Precision Sound Level Meter (Bruel & Kjaer Type 2204), with a C scale setting, was used to establish the overall sound pressure level values for the phonemes projected from the Bimorph into the sound field. The sound level meter was positioned approximately three inches over the Bimorph. The highest reading was yielded by the /ɔ/ phoneme; it registered 54 dB SPL.

APPENDIX 7

SUBJECT THRESHOLD DATA FORM

APPENDIX 7

SUBJECT THRESHOLD DATA FORM

SUBJECT RESPONSE FORM

SUBJECT:______________________________ DATE:_______________

SPEAKER:_______________ PRESSURE:__________

- THRESHOLD DATA -

Phoneme	Ascending	Descending	Ascending	Descending	Mean
u					
ʌ					
ɑ					
n					
b					
h					

Figure 17. Subject Threshold Data Form

APPENDIX 8

EQUIPMENT CALIBRATION

APPENDIX 8

EQUIPMENT CALIBRATION

The Maico MA-24 audiometer was calibrated to the Bimorph by taking voltage measurements across the electrical terminals of the Bimorph. The Tektronix 561A Oscilloscope was used in making the measurements. The stimulus tone was a 1,000 Hz calibration tone from one of the experimental tapes.

Measurements were as follows:

Attenuator dial setting	Voltage readings
30 dB	0.5 v
40	1.6
50	4.9
60	15.0
70	48.0
80	150.0

The linearity of the MA-24 audiometer dial was evaluated utilizing the Sound Level Meter (Bruel & Kjaer Type 2204S) together with the Artificial Ear (Bruel & Kjaer Type 4152). The TDH-39 earphone, housed in a MX 41/AR biscuit type cushion was connected to the 6 cc coupler of the artificial ear and this was in turn coupled to the sound level meter.

Measurements were as follows:

Attenuator dial setting	Output Error
100 dB	no error
90	+ 1.0
80	+ 1.0
70	+ 1.0
60	+ 1.0
50	+ 1.5
40	+ 1.5
30	+ 1.5
20	+ 1.5
Vernier (1 dB steps)	
61 dB	+ 0.20
62	+ 0.20
63	+ 0.10
64	+ 0.10
65	no error

APPENDIX 9

ORDER OF SPEAKER PRESENTATION

APPENDIX 9

ORDER OF SPEAKER PRESENTATION

Although the order in which the five pressure levels were presented to the subjects was a constant, it was deemed advisable to randomly distribute the order of presentation of speakers from one experimental session to another. Five possible speaker orders were generated, one for each pressure, in such a way that each speaker's presentation in each position was distributed as equally as possible. The five speaker orders are seen in Table 16.

Table 16. Five Speaker Orders

Speaker Order 1	Speaker Order 2	Speaker Order 3	Speaker Order 4	Speaker Order 5
Female Child	Male Child	Female Adult	Male Adult	Female Adult
Female Adult	Female Child	Male Adult	Male Child	Female Child
Male Child	Male Adult	Female Child	Female Adult	Male Adult
Male Adult	Female Adult	Male Child	Female Child	Male Child

It was decided to have all subjects receive the same sets of speaker orders, but that they should be distributed over the pressures in such a way that the subject's responses to pressure would not be systematically related to speaker order. The speaker order sequence for each of the four subjects was randomly determined. The individual assignments of speaker orders to each pressure can be seen in Table 17.

Table 17. Speaker Order Assignments to Subjects

Subject	Pressure				
	5 grams	10 grams	15 grams	20 grams	25 grams
1	Order 4	Order 5	Order 3	Order 2	Order 1
2	Order 1	Order 2	Order 5	Order 3	Order 4
3	Order 3	Order 1	Order 2	Order 4	Order 5
4	Order 5	Order 3	Order 4	Order 1	Order 2

APPENDIX 10

RAW DATA: SUBJECT THRESHOLD RESPONSES

APPENDIX 10

RAW DATA: SUBJECT THRESHOLD RESPONSES

Table 18. Subject One Raw Data: 5 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	X̄
Male Adult	u	17	13	15	13	14.5
	ʌ	17	16	18	13	16.0
	ɑ	20	15	17	15	16.8
	n	27	25	26	22	25.0
	b	33	34	34	32	33.3
Female Adult	u	17	13	17	14	15.3
	ʌ	18	16	19	15	17.0
	ɑ	16	14	14	12	14.0
	n	27	24	25	25	25.3
	b	35	35	34	35	34.8
Male Child	u	15	13	16	14	14.5
	ʌ	18	17	17	15	16.8
	ɑ	20	16	21	17	18.5
	n	26	22	23	22	23.3
	b	30	28	27	25	27.5
Female Child	u	25	23	26	27	25.3
	ʌ	24	23	25	25	24.3
	ɑ	27	26	27	26	26.5
	n	35	35	34	32	34.0
	b	40	40	40	40	40.0

* Ascending

** Descending

Table 19. Subject One Raw Data: 10 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	15	15	16	12	14.5
	ʌ	16	16	16	15	15.8
	ɑ	18	15	19	17	17.3
	n	31	26	28	25	27.5
	b	33	34	35	33	33.8
Female Adult	u	7	5	6	6	6.0
	ʌ	6	3	8	3	5.0
	ɑ	8	5	8	6	7.3
	n	16	15	16	12	14.8
	b	30	30	29	30	29.8
Male Child	u	14	14	14	15	14.3
	ʌ	14	15	15	13	14.3
	ɑ	17	18	19	16	17.5
	n	29	27	28	29	28.3
	b	33	30	33	33	32.3
Female Child	u	13	12	13	12	12.5
	ʌ	16	11	13	13	13.3
	ɑ	15	10	15	13	13.3
	n	23	20	24	21	22.0
	b	25	22	27	25	24.8

* Ascending

** Descending

Table 20. Subject One Raw Data: 15 Grams

Speaker	Phoneme	A*	D**	Thresholds A	D	$\bar{X}$
Male Adult	u	10	7	11	7	8.8
		11	8	15	13	11.8
		12	9	10	9	10.0
	n	20	19	22	19	20.0
	b	29	25	29	27	27.5
Female Adult	u	11	9	10	9	9.8
		8	7	9	6	7.5
		11	7	10	5	8.3
	n	16	15	15	15	15.3
	b	27	28	33	28	29.0
Male Child	u	11	8	7	6	8.0
		7	5	6	5	5.8
		16	15	16	15	15.5
	n	20	21	19	18	19.5
	b	25	21	21	19	21.5
Female Child	u	11	5	8	6	7.5
		11	11	9	7	9.5
		11	7	7	9	8.5
	n	16	13	12	14	13.8
	b	18	17	18	19	18.0

* Ascending

** Descending

Table 21. Subject One Raw Data: 20 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	X̄
Male Adult	u	11	8	10	8	9.3
	ʌ	11	7	8	6	8.0
	ɑ	10	10	10	12	10.5
	n	20	18	20	18	19.0
	b	36	31	32	32	32.8
Female Adult	u	5	5	6	6	5.5
	ʌ	8	5	6	3	5.5
	ɑ	9	8	7	7	7.8
	n	14	17	15	15	15.3
	b	33	28	28	29	29.5
Male Child	u	1	0	5	3	2.3
	ʌ	5	6	6	4	5.3
	ɑ	5	6	7	5	5.8
	n	20	14	17	14	16.3
	b	22	22	25	22	22.8
Female Child	u	6	2	3	0	2.8
	ʌ	3	0	4	-1	1.5
	ɑ	3	5	3	4	3.8
	n	18	16	15	12	15.3
	b	20	15	17	12	16.0

* Ascending

** Descending

Table 22. Subject One Raw Data: 25 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	13	7	13	7	10.0
	ʌ	11	9	16	13	12.3
	ɑ	12	12	13	9	11.5
	n	24	19	24	21	22.0
	b	30	29	32	30	30.3
Female Adult	u	8	6	11	8	8.3
	ʌ	11	10	9	10	10.0
	ɑ	10	5	8	7	7.5
	n	17	16	18	19	17.5
	b	28	29	27	27	27.8
Male Child	u	4	4	8	8	6.0
	ʌ	7	6	7	5	6.3
	ɑ	7	8	8	5	7.0
	n	17	18	23	15	18.3
	b	22	22	24	22	22.5
Female Child	u	2	-2	0	-1	-0.2
	ʌ	0	1	2	0	0.8
	ɑ	6	3	5	2	4.0
	n	14	11	14	11	12.5
	b	21	18	20	18	19.3

* Ascending

** Descending

Table 23. Subject Two Raw Data: 5 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	X̄
Male Adult	u	11	7	10	9	9.3
	ʌ	12	9	9	10	10.0
	ɑ	12	10	11	11	11.0
	n	20	18	21	20	19.8
	b	28	26	28	27	27.3
Female Adult	u	9	7	6	6	7.0
	ʌ	10	7	9	9	8.8
	ɑ	6	2	5	3	4.0
	n	16	14	13	14	14.3
	b	24	26	24	25	24.8
Male Child	u	10	10	12	10	10.5
	ʌ	12	9	10	9	10.0
	ɑ	14	15	15	10	13.5
	n	22	21	22	18	20.8
	b	26	22	25	24	24.3
Female Child	u	10	7	8	9	8.5
	ʌ	6	4	6	1	4.3
	ɑ	6	5	7	6	4.3
	n	16	13	14	14	14.3
	b	21	16	19	18	18.5

* Ascending

** Descending

Table 24. Subject Two Raw Data: 10 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\overline{X}$
Male Adult	u	20	17	19	20	19.0
	ʌ	18	17	19	19	18.3
	ɑ	21	22	21	20	21.0
	n	29	28	28	29	28.5
	b	38	34	38	37	36.8
Female Adult	u	21	21	20	20	20.5
	ʌ	21	21	20	21	20.8
	ɑ	21	18	20	20	19.8
	n	29	30	30	30	29.8
	b	38	38	40	39	38.3
Male Child	u	22	20	22	23	21.8
	ʌ	19	16	15	15	16.3
	ɑ	24	23	24	24	23.8
	n	30	29	30	28	29.3
	b	34	33	34	32	33.3
Female Child	u	30	30	30	31	30.3
	ʌ	28	27	28	27	27.5
	ɑ	29	31	31	29	30.0
	n	39	39	40	39	39.3
	b	40	40	40	40	40.0

* Ascending

** Descending

Table 25. Subject Two Raw Data: 15 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	17	13	15	13	14.5
	ʌ	15	14	13	12	13.5
	ɑ	15	14	14	13	14.0
	n	21	20	22	20	20.8
	b	31	30	34	30	31.3
Female Adult	u	19	16	19	14	17.0
	ʌ	13	13	14	8	12.0
	ɑ	14	10	12	12	12.0
	n	23	19	19	17	19.5
	b	31	28	33	29	30.3
Male Child	u	12	9	12	10	10.8
	ʌ	12	10	14	9	11.3
	ɑ	20	16	16	15	16.8
	n	20	20	21	18	19.8
	b	23	19	22	22	21.5
Female Child	u	27	27	27	25	26.5
	ʌ	24	21	23	21	22.3
	ɑ	29	24	27	26	26.5
	n	34	26	29	28	29.3
	b	33	30	32	29	31.0

* Ascending

** Descending

Table 26. Subject Two Raw Data: 20 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	19	18	20	19	19.0
	ʌ	19	21	19	19	19.5
	ɑ	22	22	21	21	21.5
	n	29	31	30	31	30.3
	b	37	39	38	38	38.0
Female Adult	u	20	18	19	17	18.5
	ʌ	19	15	17	17	17.0
	ɑ	21	16	18	19	18.5
	n	28	27	30	27	28.0
	b	40	38	40	39	39.3
Male Child	u	24	26	25	26	25.3
	ʌ	22	21	23	22	22.0
	ɑ	26	25	27	28	26.5
	n	37	36	36	34	35.8
	b	38	37	39	38	38.0
Female Child	u	31	32	32	31	31.5
	ʌ	27	26	30	29	28.0
	ɑ	31	30	33	30	31.0
	n	39	38	38	38	38.3
	b	40	40	40	40	40.0

* Ascending

** Descending

Table 27. Subject Two Raw Data: 25 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	19	18	18	17	18.0
	ʌ	20	19	19	19	19.3
	ɑ	20	18	19	19	19.0
	n	30	29	32	30	30.3
	b	37	36	36	36	36.3
Female Adult	u	20	20	21	19	20.0
	ʌ	20	18	20	17	18.8
	ɑ	20	19	20	17	19.0
	n	29	29	31	27	29.0
	b	39	37	40	37	38.3
Male Child	u	24	21	23	22	22.5
	ʌ	21	19	20	17	19.3
	ɑ	25	22	26	24	24.3
	n	32	32	32	31	31.8
	b	36	36	37	34	35.8
Female Child	u	31	29	29	29	29.5
	ʌ	27	26	27	25	26.3
	ɑ	29	28	30	28	28.8
	n	39	39	39	39	39.0
	b	40	40	40	40	40.0

* Ascending

** Descending

Table 28. Subject Three Raw Data: 5 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	17	17	17	16	16.8
	ʌ	20	17	19	16	18.0
	ɑ	17	15	16	11	14.8
	n	29	23	27	22	25.3
	b	38	34	37	36	36.3
Female Adult	u	18	18	17	17	17.5
	ʌ	16	15	14	14	14.8
	ɑ	16	15	15	13	14.8
	n	26	22	25	23	24.0
	b	37	35	36	35	35.8
Male Child	u	18	16	18	17	17.3
	ʌ	18	16	15	12	15.3
	ɑ	17	15	18	13	15.8
	n	27	21	25	21	23.5
	b	31	27	31	26	28.8
Female Child	u	13	12	17	12	13.5
	ʌ	19	13	18	15	16.3
	ɑ	20	15	19	15	17.3
	n	27	24	26	20	24.3
	b	32	31	31	26	30.0

* Ascending

** Descending

Table 29. Subject Three Raw Data: 10 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	19	15	16	14	16.0
	ʌ	16	11	16	14	14.3
	ɑ	18	14	12	10	13.5
	n	28	24	28	25	26.3
	b	35	34	37	38	36.0
Female Adult	u	16	12	12	10	12.5
	ʌ	15	12	13	12	13.0
	ɑ	12	9	11	10	10.5
	n	25	22	23	20	22.5
	b	33	33	33	34	33.3
Male Child	u	17	16	17	15	16.3
	ʌ	15	13	15	16	14.8
	ɑ	19	14	18	16	16.8
	n	27	25	26	25	25.8
	b	31	26	32	28	29.3
Female Child	u	18	16	18	14	16.5
	ʌ	15	13	16	12	14.0
	ɑ	15	16	15	15	15.3
	n	23	20	26	20	22.3
	b	25	22	24	23	23.5

* Ascending

** Descending

Table 30. Subject Three Raw Data: 15 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	15	13	18	15	15.3
	ʌ	18	16	17	15	16.5
	ɑ	18	16	18	16	17.0
	n	29	28	28	27	28.0
	b	39	38	39	39	38.8
Female Adult	u	18	13	16	12	14.8
	ʌ	22	18	17	16	18.3
	ɑ	17	15	16	12	15.0
	n	27	23	25	24	24.8
	b	39	38	40	40	39.3
Male Child	u	19	16	17	18	17.5
	ʌ	17	16	17	16	16.5
	ɑ	19	18	17	17	17.8
	n	23	24	23	22	23.0
	b	28	30	32	30	30.0
Female Child	u	17	17	17	15	16.5
	ʌ	23	20	20	19	20.5
	ɑ	21	20	23	20	21.0
	n	28	26	26	25	26.3
	b	31	30	31	32	31.0

* Ascending

** Descending

Table 31. Subject Three Raw Data: 20 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	16	17	18	16	16.8
	ʌ	19	15	17	17	17.0
	ɑ	18	16	16	18	17.0
	n	29	26	27	27	27.3
	b	39	36	38	34	36.8
Female Adult	u	13	9	13	8	10.8
	ʌ	14	12	15	11	13.0
	ɑ	12	9	10	8	9.8
	n	21	18	25	19	20.8
	b	34	32	36	32	33.5
Male Child	u	18	15	16	13	15.5
	ʌ	15	16	18	16	16.3
	ɑ	16	18	19	16	17.3
	n	26	24	26	23	24.8
	b	28	26	27	27	27.0
Female Child	u	15	13	15	12	13.8
	ʌ	16	14	16	13	14.8
	ɑ	21	14	18	13	16.5
	n	23	19	21	23	21.5
	b	25	21	26	21	23.3

* Ascending

** Descending

Table 32. Subject Three Raw Data; 25 Grams

Speaker	Phoneme	Threshold A*	D**	A	D	$\bar{X}$
Male Adult	u	24	19	23	20	21.5
	ʌ	21	18	23	20	20.5
	ɑ	20	19	20	17	19.0
	n	34	31	34	31	32.5
	b	40	39	40	40	39.8
Female Adult	u	22	20	23	20	21.2
	ʌ	24	22	22	19	21.8
	ɑ	24	19	22	20	21.3
	n	35	30	32	30	31.8
	b	37	39	40	39	38.8
Male Child	u	25	24	25	24	24.5
	ʌ	22	21	23	21	21.8
	ɑ	27	25	27	25	26.0
	n	36	35	36	34	35.3
	b	39	37	40	37	38.3
Female Child	u	26	25	27	25	25.8
	ʌ	24	24	24	22	23.5
	ɑ	25	25	26	26	25.5
	n	35	34	35	32	34.0
	b	37	37	40	37	37.8

* Ascending

** Descending

Table 33. Subject Four Raw Data: 5 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\overline{X}$
Male Adult	u	10	8	8	6	8.0
	ʌ	12	9	10	11	10.5
	ɑ	12	10	13	13	12.0
	n	22	20	23	22	21.8
	b	31	31	32	30	31.0
Female Adult	u	13	10	14	10	11.8
	ʌ	13	10	8	8	9.8
	ɑ	11	9	9	9	9.5
	n	21	18	20	20	19.8
	b	29	29	31	29	29.5
Male Child	u	10	10	11	10	10.3
	ʌ	11	8	9	9	9.3
	ɑ	10	10	10	9	9.8
	n	21	21	21	20	20.8
	b	26	25	27	22	25.0
Female Child	u	7	8	10	9	8.5
	ʌ	10	7	9	9	8.8
	ɑ	11	12	13	13	12.3
	n	20	16	19	16	17.8
	b	20	20	22	20	20.5

* Ascending

** Descending

Table 34. Subject Four Raw Data: 10 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	13	12	14	13	13.0
	ʌ	14	12	14	12	15.5
	ɑ	11	8	10	8	9.3
	n	29	28	29	27	28.3
	b	36	37	36	34	35.8
Female Adult	u	12	12	13	9	11.5
	ʌ	12	8	10	8	9.5
	ɑ	9	11	10	6	9.0
	n	24	24	24	21	23.3
	b	37	35	35	35	35.5
Male Child	u	12	10	13	11	11.5
	ʌ	11	9	13	11	11.0
	ɑ	15	12	15	10	13.0
	n	25	22	23	19	22.8
	b	28	29	29	28	28.5
Female Child	u	13	10	11	10	11.0
	ʌ	11	8	11	8	9.5
	ɑ	12	8	10	10	10.0
	n	17	16	18	17	17.0
	b	24	20	24	19	21.8

* Ascending

** Descending

Table 35. Subject Four Raw Data: 15 Grams

Speaker	Phoneme	A*	D**	A	D	$\bar{X}$
Male Adult	u	13	11	13	12	12.3
	ʌ	14	9	12	11	11.5
	ɑ	12	8	11	9	10.0
	n	24	21	22	22	22.3
	b	29	29	28	31	29.3
Female Adult	u	11	9	9	9	9.5
	ʌ	5	3	5	5	4.5
	ɑ	8	7	7	5	6.8
	n	20	20	21	19	20.0
	b	32	33	35	30	32.5
Male Child	u	9	6	10	8	8.3
	ʌ	13	10	12	10	11.3
	ɑ	13	9	12	10	11.0
	n	23	19	24	19	21.3
	b	26	25	30	26	26.8
Female Child	u	11	10	9	9	9.8
	ʌ	11	7	9	6	8.3
	ɑ	10	12	13	10	11.3
	n	21	21	19	17	19.5
	b	22	21	22	22	21.8

* Ascending

** Descending

Table 36. Subject Four Raw Data: 20 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\bar{X}$
Male Adult	u	16	15	14	14	15.0
	ʌ	16	14	14	16	15.0
	ɑ	14	14	15	13	14.3
	n	27	24	25	24	25.0
	b	33	34	34	32	33.3
Female Adult	u	13	11	14	11	12.3
	ʌ	14	11	11	11	11.8
	ɑ	7	7	7	6	6.8
	n	22	17	19	17	18.8
	b	31	29	32	33	31.3
Male Child	u	15	12	16	14	14.3
	ʌ	14	13	14	11	13.0
	ɑ	13	9	13	10	11.3
	n	24	23	23	23	23.3
	b	28	26	27	27	27.0
Female Child	u	13	11	11	11	11.5
	ʌ	14	12	14	10	12.5
	ɑ	16	15	13	12	14.0
	n	22	21	20	19	20.5
	b	23	22	24	22	22.8

* Ascending

** Descending

Table 37. Subject Four Raw Data: 25 Grams

Speaker	Phoneme	Thresholds A*	D**	A	D	$\overline{X}$
Male Adult	u	9	6	9	10	8.5
	ʌ	11	13	13	12	12.3
	ɑ	10	11	12	12	11.3
	n	22	18	19	16	18.8
	b	32	28	30	29	29.8
Female Adult	u	11	8	10	8	9.3
	ʌ	11	8	7	8	8.5
	ɑ	11	10	9	6	9.0
	n	20	16	18	20	18.5
	b	35	32	34	35	34.0
Male Child	u	13	11	12	11	11.8
	ʌ	14	13	14	12	13.3
	ɑ	10	11	11	15	11.8
	n	21	18	17	19	18.8
	b	26	25	27	25	25.8
Female Child	u	12	8	9	9	9.5
	ʌ	11	7	10	8	9.0
	ɑ	12	9	9	7	9.3
	n	16	16	17	16	16.3
	b	24	22	22	22	22.5

* Ascending

** Descending